THE INVESTIGATION OF THE WORLD TRADE CENTER COLLAPSE: FINDINGS, RECOMMENDATIONS, AND NEXT STEPS

HEARING

BEFORE THE

COMMITTEE ON SCIENCE

ONE HUNDRED SEVENTH CONGRESS

SECOND SESSION

MAY 1, 2002

Serial No. 107–61

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CONTENTS

May 1, 2002

Page

Witness List 2

Hearing Charter 3

Opening Statements

Statement by Representative Sherwood L. Boehlert, Chairman, Committee on Science, U.S. House of Representatives 17
  Written Statement 18

Statement by Representative Ralph M. Hall, Minority Ranking Member, Committee on Science, U.S. House of Representatives 19
  Written Statement 20

Statement by Representative Anthony Weiner, Member, Committee on Science, U.S. House of Representatives 21
  Written Statement 22

Statement by Representative Constance Morella, Member, Committee on Science, U.S. House of Representatives 23
  Written Statement 24

Statement by Representative Steve Israel, Member, Committee on Science, U.S. House of Representatives 24

Statement by Representative Felix J. Grucci, Jr., Member, Committee on Science, U.S. House of Representatives 25
  Written Statement 26

Prepared Statement by Representative Sheila Jackson Lee, Member, Committee on Science, U.S. House of Representatives 26

Panel

Mr. Robert F. Shea, Acting Administrator, Federal Insurance and Mitigation Administration, Federal Emergency Management Association
  Oral Statement 28
  Written Statement 28
  Biography 29

Dr. W. Gene Corley, American Society of Civil Engineers, Chair of Building Performance Assessment Team reviewing the WTC disaster; accompanied by Dr. Jonathan Barnett, Professor, Center for Fire Safety Studies, Worcester Polytechnic Institute
  Oral Statement 29
  Written Statement 32
  Biography 44
  Financial Disclosure 46

Dr. Arden L. Bement, Jr., Director, National Institute of Standards and Technology
  Oral Statement 47
  Written Statement 50
  Summary of proposed NIST investigation plan 54
  NIST/FEMA memorandum of understanding 84
  Biography 88

Professor Glenn P. Corbett, Assistant Professor of Fire Sciences, John Jay College, New York City
  Oral Statement 89

Page
Professor Glenn P. Corbett, Assistant Professor of Fire Sciences, John Jay College, New York City—Continued
  Written Statement 92
  Biography 94
  Financial Disclosure 96

Discussion
  Evacuation/Emergency Response Procedures 97
  Access to Investigation Materials 98
  Stairwell Separation 99
  Sprinkler System Redundancy 100
  Egress Systems 100
  Building Codes 101
  WTC Building 7 101
  Stairwell Materials 103
  NIST Subpoena Power 103
  Stairwell Separation/Water System Redundancy 104
  Building Codes 106
  NIST Funding Needs 107
  Witness Comments on the National Construction Safety Team Act 109
  NIST Building Research Capabilities 112
  NIST Funding of the Investigation 114
  Fire and Building Failure 115
  WTC Building 7 116
  NIST Follow-up Investigation 118
  Building Codes/Code-Related Research 120
  NIST Subpoena Power 121
  Building Performance Information Repository 122

Appendix 1: Additional Material for the Record

Letter to Chairman Sherwood Boehlert from Mark D. Wallace, Deputy General Counsel, Federal Emergency Management Agency 126
Letter to Dr. Arden L. Bement, Jr., from Francis J. Lombardi, P.E., Chief Engineer, Port Authority of New York and New Jersey 128
Statement of the International Code Council 129
World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations, FEMA 403/May 2002 135

THE INVESTIGATION OF THE WORLD TRADE CENTER COLLAPSE: FINDINGS, RECOMMENDATIONS, AND NEXT STEPS

WEDNESDAY, MAY 1, 2002

House of Representatives,
Committee on Science,
Washington, DC.

The Committee met, pursuant to call, at 12:11 p.m., in Room 2318 of the Rayburn House Office Building, Hon. Sherwood L. Boehlert (Chairman of the Committee) presiding.

COMMITTEE ON SCIENCE
U.S. HOUSE OF REPRESENTATIVES

The Investigation of the World Trade Center Collapse: Findings, Recommendations and Next Steps

Wednesday, May 1, 2002

Noon – 3:00 PM
2318 Rayburn House Office Building

Witness List

Mr. Robert Shea
Acting Administrator,
Federal Insurance and Mitigation Administration

Dr. W. Gene Corley
American Society of Civil Engineers,
Chair of Building Performance Assessment Team reviewing the WTC disaster

Accompanied by
Dr. Jonathan Barnett
Professor, Center for Fire Safety Studies
Worcester Polytechnic Institute

Dr. Arden Bement
Director,
National Institute of Standards and Technology

Professor Glenn Corbett
Assistant Professor of Fire Sciences,
John Jay College, New York City

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HEARING CHARTER

COMMITTEE ON SCIENCE
U.S. HOUSE OF REPRESENTATIVES

The Investigation of the World Trade Center Collapse: Findings, Recommendations, and Next Steps

WEDNESDAY, MAY 1, 2002
12:00 P.M.–3:00 P.M.
2318 RAYBURN HOUSE OFFICE BUILDING

1. Purpose

On Wednesday, May 1, at noon the House Committee on Science will hold a hearing on the key findings and recommendations of the Federal Emergency Management Agency's (FEMA) investigation into the collapse of the World Trade Center (WTC). The hearing will also review the plans of the National Institute of Standards and Technology (NIST) to conduct a more extensive follow-up investigation and to establish a comprehensive research and development plan to improve standards, practices and codes for buildings and fire. In addition, the witnesses will be asked to comment on a bill to give NIST additional investigative powers.

The hearing will address the following overarching questions:

1. What are the findings and recommendations of the report of FEMA's building performance assessment team (BPAT) regarding the collapse of the World Trade Center?
2. What are NIST's plans to follow up on the recommendations of the BPAT report?
3. How should NIST be involved in investigating catastrophic building failures in the future?
4. To what extent does NIST require new authorities, such as the ability to issue subpoenas, in order to conduct investigations of building failures?

2. Issues

Since the March 6, 2002 Science Committee hearing on the collapse of the World Trade Center, FEMA has readied its report of the Trade Center disaster for release, NIST has prepared initial plans for taking the reins from FEMA to conduct its own, more extensive investigation, and the Administration has requested supplemental funding of $16 million to pay for NIST's investigation. At the same time, a number of new issues have arisen:

- **It is unclear how NIST's $16 million follow-up investigation will differ from that of the BPAT's.** While NIST has made clear the goals for its proposed follow-up investigation to collect more data on the World Trade Center disaster and has outlined the general issues it plans to probe, many aspects of the investigation remain undefined. For example, it is still unclear how much data remains to be collected or what kind of data is needed to determine whether changes in building codes are necessary.
- **It is uncertain whether NIST will receive the funding necessary to pay for its planned investigation.** The Administration's request of $16 million for further investigation of the World Trade Center disaster was made on behalf of FEMA rather than NIST. While FEMA has stated that NIST is in charge of the follow up investigation and is willing to transfer this funding to NIST, it is unclear whether it has the authority to do so. FEMA has promised to have a determination from its Office of General Counsel at the time of the hearing as to whether additional authority from Congress would be required to transfer the funds to NIST.
- **It is unclear whether the second phase of NIST's follow-up plans—a 3-year research effort to determine whether and how changes in building codes should be made—will receive the commitment for funding it requires.** In addition to conducting a $16 million follow-up inves-

tigation to collect more data regarding the Trade Center disaster, NIST also proposes to conduct longer-term research on issues identified by the BPAT report. For example, NIST plans to develop computer models of the collapse and conduct experiments to better understand the effect of fire on steel connections in buildings. So far, the Administration has requested $2 million in the FY03 budget for this type of research and NIST has committed an additional $2 million next year from amounts that otherwise would go to its building and fire laboratory, the principal lab that will do the research in any case. NIST estimates, however, that the total cost of the program will be approximately $40 million over the next three years. While NIST has said that some funds may be contributed by private sources, it is unclear if any such commitments have been made. If adequate funding for NIST's research efforts are not secured it is unclear how NIST will use the information it collects in its investigation to improve standards, practices and codes for buildings and fire.

- **It is unclear what role NIST will play in investigating future building failures.** FEMA received heavy criticism at the last Science Committee hearing for shortcomings in the way in which it conducted the investigation of the collapse of the World Trade Center. Following the hearing, FEMA entered into a memorandum of understanding (MOU) with NIST to enlist NIST's support in future investigations. The details of that MOU have not yet been worked out, and it is unclear what kinds of building collapses, if any, will lead FEMA to ask for NIST's assistance in the future.
- **NIST may require additional authorities to carry out an effective building investigation.** FEMA's investigation into the World Trade Center collapse was inhibited at several turns by an inability to access the disaster site quickly, preserve evidence, and obtain necessary documentary evidence, such as blueprints, in a timely way. Several observers, including the families of the Trade Center victims, have called for World Trade Center investigators to be granted authorities akin to those of the National Transportation Safety Board (NTSB), which is authorized by statute to enter the site of airplane crashes, preserve evidence, and issue subpoenas to witnesses or for documents to facilitate its investigation.

3. Background

On September 11, 2001, terrorists crashed two fuel-laden commercial Boeing 767 airplanes into the north and south towers of the World Trade Center complex in New York City. Although each building withstood the initial impact, both suffered complete collapse within two hours. While more than 25,000 people were successfully evacuated from the towers, nearly 3,000 building occupants and emergency responders died when the buildings fell.

FEMA responded to this disaster by deploying a building performance assessment team (BPAT)—a group of experts in engineering, design, construction, and building codes—to conduct a formal analysis of the causes of the collapse of the buildings and determine what can be learned from the disaster to save lives in the future. Concerns regarding the timing of the BPAT deployment, their access to the site and building records, premature disposal of evidence, and FEMA's lack of regular communication with the public were the subject of a previous Science Committee hearing, and are explained in detail in Appendix 1 (the March 6 hearing charter).

FEMA and the American Society of Civil Engineers (ASCE), the organization heading up the WTC BPAT, will announce the results and recommendations of the BPAT report at the hearing. Preliminary drafts of the report reveal that despite the massive impacts that punctured the building's exterior frame of support, the buildings were able to successfully redistribute the weight from higher floors and remain standing. However, the fires in the buildings, fed by jet fuel and flammable building contents, proved too intense, producing at their peak an amount of energy equivalent to the output of a typical nuclear power plant. The fires caused the steel, stripped of its fireproofing by the impact of the planes, to weaken and buckle. With water pipes for fire suppression systems severed, the fires led to the eventual progressive collapse of the buildings.

The report highlights potential reasons for why the two towers, almost identical in design, performed differently under the stresses of the disaster. It also identifies critical features that enabled so many to evacuate, and the design elements that may have played a role in the collapse and prevented people above the impacts from being able to exit the buildings. (See a March 29th article from *The New York Times,* which is attached as Appendix 2, for further discussion of the BPAT's findings and recommendations.)

The report also calls for further study of several issues that were beyond the scope of the BPAT investigation. For example, the report recommends developing methods to predict performance of building materials in fires, improving existing models of how fires spread, analyzing the WTC evacuation and proposing improvements to evacuation procedures for tall buildings, involving engineers in the processes that emergency personnel use to develop plans for hazard assessment, etc. The report also outlines specific needs for further investigation into the performance strengths and weaknesses of each building within the WTC complex.

NIST Investigation and Research Program

NIST's Building and Fire Research Laboratory (BFRL) carries out research in fire science, fire safety engineering, and structural, mechanical, and environmental engineering. It is the only federal laboratory dedicated to research on building design and fire safety.

In January, FEMA asked NIST to take over the next phase of the investigation of the collapse essentially to build upon the BPAT recommendations and conduct a more thorough investigation of the events leading to the collapse. While waiting for the BPAT report to be released, NIST has developed a two-part strategy: investigation and long-term research.

First, NIST will conduct a $16 million comprehensive and thorough two-year investigation to determine, through a technical analysis, why and how WTC 1, 2 and 7 collapsed. The investigation will cover subjects including evacuation, standards that were used in the construction and maintenance of the buildings, and whether new technologies for future buildings could reduce the risk of collapse. For example, the fire-performance of steel trusses and connectors with spray-applied fireproofing is not well understood, but may have been critical to the ultimate failure of the Trade Center. NIST will purchase floor trusses similar to those in the WTC 1 & 2, spray on fireproofing as it was done in the buildings, and subject them to fire and mechanical conditions (vibrations and impacts) like those experienced on September 11. Information from these tests not only can answer questions about the exact nature of the collapse of the buildings, but also will serve as the foundation for developing performance-based criteria for fireproofing steel, which is a part of NIST's long-term research agenda.

While the first part of the strategy specifically focuses on investigating the collapse of the World Trade Center buildings 1, 2, and 7, NIST believes that many of the "lessons learned" through a technical investigation can have broad applicability to building design. NIST is developing a public-private research plan to focus on many of the long-term research needs that the BPAT report recommended. NIST estimates that this program could cost approximately $40 million over the next three years. The Administration has already requested $2 million in the FY03 budget and NIST has committed another $2 million by shifting funding in the BFRL's base funding level to this purpose. The public-private program will address four national needs:

- To develop a better understanding the response of structures and materials to fire, and options for improving the safety of existing buildings;
- To develop a better understanding human behavior in emergency evacuations, including exploring technologies to assist mobility-impaired people, and to develop standards for the equipment that fire and emergency responders use;
- To reduce the vulnerability of buildings to chemical, biological, and radiological attacks; and
- To develop a roadmap for changes to building codes, standards and designs, and for disseminating research to industry.

Calls for New Authorities for NIST

While NIST is optimistic that the investigation combined with the research plan can ultimately lead to changes in building codes, standards and practices, as well as improvements in emergency response and evacuation procedures, some NIST officials agree with families of Trade Center victims that NIST needs new authorities in order to conduct an effective investigation. They believe that, like the National Transportation Safety Board, NIST should have the authority to issue subpoenas to obtain critical documents or persuade unwilling witnesses to provide information important to the investigation. Proponents of granting NIST subpoena power point to the fact that the BPAT team had requested but were denied several kinds of documentary evidence to assist its investigation, such as the recordings of emergency responders and 911 calls made that could help investigators determine what was happening inside the World Trade Center buildings before they collapsed on September 11.

4. Witnesses

The following witnesses will address the Committee:

Mr. Robert Shea, Acting Administrator, Federal Insurance and Mitigation Administration, Federal Emergency Management Agency

Dr. W. Gene Corley, P.E., S.E., American Society of Civil Engineers, Chair of Building Performance Assessment Team reviewing the World Trade Center disaster

Dr. Arden Bement, Director, National Institute of Standards and Technology

Professor Glenn Corbett, Assistant Professor of Fire Science at John Jay College, New York City

5. Questions

The witnesses were asked to address the following issues before the Committee:

Mr. Shea:

Instead of formally testifying before the Committee, Mr. Shea will officially release the results of the BPAT study of the World Trade Center disaster and remain on the panel to respond to questions.

Dr. Corley:

Dr. Corley was asked to describe the key findings and recommendations of the World Trade Center Building Performance Study. His focus is to be on any "lessons learned" from the collapse, any recommendations to alter building codes, standards or practices, and any recommendations to which the National Institute of Standards and Technology, in its follow-up investigation and study, should be especially attentive.

The Committee posed the following questions for Dr. Corley to address in his written testimony:

- What areas critically need further study but lie outside the scope of your report?
- What additional data collecting and modeling must be done in order to derive "lesson learned" from this disaster and who should do this work?
- What barriers stand in the way of having the recommendations of the BPAT adopted in the building codes community and how can these barriers be overcome?
- What work, if any, does ASCE plan to conduct, as follow-up to this study, to develop any changes to building practices, standards and codes?

Dr. Bement:

Dr. Bement was asked to describe the $16 million investigation that NIST proposes to conduct into the World Trade Center disaster, with particular attention to the following: How will the investigation differ from, and follow up on the Federal Emergency Management Agency's BPAT study of the WTC disaster?

The Committee also requested that he describe NIST's proposal to follow the investigation with additional research, with particular attention to:

- How will NIST's proposed research program differ from the investigation?
- How will the research effort or the investigation lead to changes in building standards, practices and codes?
- What additional authorities, if any, will NIST need in order to conduct a complete and through investigation?
- What specific steps is NIST taking to ensure that NIST communicates its plans to the public and professional communities?

Professor Corbett:

Professor Corbett was asked to evaluate the NIST's proposed study with particular attention to the following questions:

- Based on your current understanding of the areas that NIST plans to cover in its proposed investigation and follow-up research plan, how should NIST ensure that all of the areas (especially ones outside of the Agency's traditional expertise) are adequately addressed in its plan?
- How should NIST implement its investigation to ensure that its conclusions are definitive, defensible, and most useful in helping to improve building codes, fire safety standards, etc?

- What additional authorities, if any, do you think NIST must have in order to conduct a thorough and effective investigation, and why?

6. Appendices

Appendix 1:

Hearing charter: "Learning from 9/11: Understanding the Collapse of the World Trade Center," Committee on Science, U.S. House of Representatives, March 6, 2002.

Appendix 2:

The New York Times article from March 29, 2002: "Towers Withstood Impact, But Fell to Fire, Report Says" by James Glanz and Eric Lipton. p. A1.

Appendix 1

HEARING CHARTER

COMMITTEE ON SCIENCE
U.S. HOUSE OF REPRESENTATIVES

Learning from 9/11—Understanding the Collapse of the World Trade Center

WEDNESDAY, MARCH 6, 2002
12:00 P.M.–2:00 P.M.
2318 RAYBURN HOUSE OFFICE BUILDING

I. Purpose

On Wednesday, March 6, at noon the House Committee on Science will hold a hearing on the investigation into the collapse of the World Trade Center (WTC). Witnesses from industry, academia, and government will testify on the catastrophic collapse of the WTC complex and subsequent efforts by federal agencies and independent researchers to understand how the building structures failed and why. By scrutinizing the steel and other debris, blueprints and other documents, and recorded images of the disaster, engineers, designers, and construction professionals may learn valuable lessons that could save thousands of lives in the event of future catastrophes, natural or otherwise.

The Committee plans to explore several overarching questions raised by the collapse and the ensuing investigation:

1. What have we learned about how the Federal Government investigates catastrophic building collapses, and are any changes warranted?
2. What have we learned about the collapse of the World Trade Center, including which structural elements failed first, and why?
3. How will we know what changes, if any, are warranted in building and fire codes as a result of lessons learned from the World Trade Center's collapse?
4. Has the World Trade Center disaster exposed any gaps in our understanding of buildings and fire, and are changes needed in the Federal Government's research agenda?

2. Background

At 8:47 a.m. on the morning of September 11, 2001, terrorists crashed a fuel-laden Boeing 767 into the north tower (Tower 1) of the World Trade Center (WTC) complex. Approximately 16 minutes later, a second Boeing 767 slammed into the south tower (Tower 2), exploding upon impact and engulfing several of the building's upper floors in flames. While the performance of both towers exceeded their design specifications—the buildings were designed to withstand the force from the initial impact of a 707 jet—the subsequent structural and fire damage still caused the buildings to fall. Tower 2 collapsed in less than an hour, killing victims trapped above the flames and rescue workers in and around the building. Thirty minutes later, Tower 1 met the same fate. While more than 25,000 people were successfully evacuated from the towers, nearly 3,000 people and emergency responders were killed in the collapses. As the day progressed, the remaining WTC buildings collapsed as well, including Building 7, which burned for 8 hours before crumbling to the ground. Fortunately, the later building collapses produced no casualties.

In the wake of the collapses, search and rescue workers launched an around-the-clock recovery effort to find and recover survivors and victims who perished. To make way, literally tons of twisted steel and fractured concrete were removed from the rubble pile and loaded onto convoys of bulldozers and flatbed trucks to be carried away to recycling plants and landfills.

Researchers also began to respond immediately. Among the first were National Science Foundation (NSF)-funded social scientists and engineers who arrived at the WTC site within 48 to 72 hours after the tragedy to begin collecting data. Similarly, the American Society of Civil Engineers (ASCE) formed a Disaster Response Team within hours of the first plane strike. On September 12th, the Federal Emergency Management Agency (FEMA) and its contractor, Greenhorne and O'Mara, Inc., located in Greenbelt, Maryland, commenced the development of a Building Performance Assessment Team (BPAT; explained more fully on the next page) to conduct a formal analysis of the progressive collapses and produce a report of its findings. A variety of other engineering researchers and professionals, including members of the Structural Engineering Association of New York, also engaged in the monumental task of collecting data that could lead to a better understanding of the collapse of the buildings themselves and to the development of mitigation strategies to prevent a similar tragedy in the future.

Concerns Related to the Engineering Investigation

Though many of the individuals who have participated in the WTC building performance investigation are architects and engineers with experience investigating other structural collapses—including those resulting from natural causes as well as terrorist attacks—nothing had prepared these investigators for a disaster of this magnitude and complexity. Unlike the destruction caused by an earthquake, which may affect several buildings across an expansive area, this disaster involved many buildings and a massive debris pile in a small, confined area. Also unlike most earthquakes, the WTC disaster caused significant casualties and prompted a prolonged search and rescue effort. In addition, the concurrent criminal investigation by the Federal Bureau of Investigation and a separate investigation by the National Transportation Safety Board further frustrated the building performance investigators.

The investigation has been hampered by a number of issues, including:

- **No clear authority and the absence of an effective protocol for how the building performance investigators should conduct and coordinate their investigation with the concurrent search and rescue efforts, as well as any criminal investigation:** Early confusion over who was in charge of the site and the lack of authority of investigators to impound pieces of steel for examination before they were recycled led to the loss of important pieces of evidence that were destroyed early during the search and rescue effort. In addition, a delay in the deployment of FEMA's BPAT team may have compounded the lack of access to valuable data and artifacts.
- **Difficulty obtaining documents essential to the investigation, including blueprints, design drawings, and maintenance records:** The building owners, designers and insurers, prevented independent researchers from gaining access—and delayed the BPAT team in gaining access—to pertinent building documents largely because of liability concerns. The documents are necessary to validate physical and photographic evidence and to develop computer models that can explain why the buildings failed and how similar failures might be avoided in the future.
- **Uncertainty as a result of the confidential nature of the BPAT study:** The confidential nature of the BPAT study may prevent the timely discovery of potential gaps in the investigation, which may never be filled if important, but ephemeral evidence, such as memories or home videotapes, are lost. The confidentiality agreement that FEMA requires its BPAT members to sign has frustrated the efforts of independent researchers to understand the collapse, who are unsure if their work is complementary to, or duplicative of, that of the BPAT team. In addition, the agreement has prevented the sharing of research results and the ordinary scientific give-and-take that otherwise allows scientists and engineers to winnow ideas and strengthen results.
- **Uncertainty as to the strategy for completing the investigation and applying the lessons learned:** The BPAT team does not plan, nor does it have sufficient funding, to fully analyze the structural data it collected to determine the reasons for the collapse of the WTC buildings. (Its report is expected to rely largely on audio and video tapes of the event.) Nor does it plan to examine other important issues, such as building evacuation mechanisms. Instead, FEMA has asked the National Institute of Standards and Technology (NIST) to take over the investigation. Yet so far, NIST has not released a detailed plan describing how it will take over the investigation, what types of analyses it will conduct, how it will attempt to apply the lessons it learns to try to improve building and fire codes, and how much funding it will require.

Role of the Federal Emergency Management Agency

The Federal Emergency Management Agency is charged with supporting the Nation's emergency management system. FEMA intervenes at all stages of disaster management including preparation, response, recovery, mitigation, risk reduction, and prevention. In the case of the World Trade Center attack, FEMA dispatched

Urban Search and Rescue Teams and established a disaster field office at the site within hours of the first strike to assist in New York City's rescue effort. At the same time, the FEMA Building Performance Assessment Team (BPAT) began their important work of initiating an analysis that could ultimately yield valuable information about the sequence of events and failures that resulted in progressive building collapse.

BPATs are routinely deployed by FEMA following disasters caused by events such as floods and hurricanes. The teams are formed by, and operate under the direction of the Mitigation Directorate's Program Assessment and Outreach Division and comprise such individuals as regional FEMA staff, representatives from state and local governments, consultants who are experts in engineering, design, construction, and building codes, and other technical and support personnel. A contractor for FEMA, Greenhorne & O'Mara, Inc., maintains a roster of hundreds of mitigation specialists from across the United States. BPAT teams are typically deployed within seven days of any disaster event.

Generally, a BPAT conducts field inspections and technical evaluations of buildings to identify design practices, construction methods, and building materials that either failed or were successful in resisting the forces imposed by the event. A major objective of the BPAT's findings and recommendations are aimed at improving design, construction and enforcement of building codes to enhance performance in future disasters. The culmination of the BPAT's efforts is a report that presents the team's observations, conclusions, and recommendations for improving building performance in future natural disasters.

The BPAT team deployed to the WTC site was assembled by the American Society of Civil Engineers and is headed by W. Gene Corley, Ph.D., P.E, Senior Vice President of Construction Technologies Laboratory in Skokie, Illinois. He was also the principal investigator in the FEMA study of Oklahoma City's Murrah Federal Office Building. On September 11th, ASCE, in partnership with a number of other professional organizations, commenced the formation of an independent team of experts to conduct a building performance assessment study at the WTC site as part of ASCE's Disaster Response Procedure. In late September, this team, the ASCE Disaster Response team, was officially appointed as the BPAT team and was funded by FEMA to assess the performance of the buildings and report its findings. The BPAT team received $600,000 in FEMA funding in addition to approximately $500,000 in ASCE in-kind contributions.

The 23-member BPAT team conducted an analysis of the wreckage on-site, at Fresh Kills Landfill and at the recycling yard from October 7–12, 2001, during which the team extracted samples from the scrap materials and subjected them to laboratory analysis. Why the analysis was conducted only after a delay of three weeks after the attacks remains unclear. Since November, members of the Structural Engineers Association of New York (SEAoNY) have volunteered to work on the BPAT team's behalf and are visiting recycling yards and landfills two to three times a week to watch for pieces of scrap that may provide important clues with regard to the behavior of the buildings.

In the month that lapsed between the terrorist attacks and the deployment of the BPAT team, a significant amount of steel debris—including most of the steel from the upper floors—was removed from the rubble pile, cut into smaller sections, and either melted at the recycling plant or shipped out of the U.S. Some of the critical pieces of steel—including the suspension trusses from the top of the towers and the internal support columns—were gone before the first BPAT team member ever reached the site. Fortunately, an NSF-funded independent researcher, recognizing that valuable evidence was being destroyed, attempted to intervene with the City of New York to save the valuable artifacts, but the city was unwilling to suspend the recycling contract. Ultimately, the researcher appealed directly to the recycling plant, which agreed to provide the researcher, and ultimately the ASCE team and the SEAoNY volunteers, access to the remaining steel and a storage area where they could temporarily store important artifacts for additional analysis. Despite this agreement, however, many pieces of steel still managed to escape inspection.

The BPAT team is expected to release its report in April. Because FEMA requires the members of its BPAT team to sign a confidentiality agreement until the report is released, the exact scope of the report is unknown. But it appears from the role that BPAT teams normally play and general comments ASCE members of the BPAT team have made that the report is likely to include an examination of how the buildings behaved leading up to the collapse, hypotheses for which structural elements failed and thereby initiated the collapse, and recommendations for additional research and analysis.

For example, ASCE has said that the study will rely primarily on audio and video recordings, interviews with survivors, blueprints and design drawings of the World

Trade Center, and evidence they or the SEAoNY volunteers have collected from the rubble. The BPAT team has access to more than 120 hours of high quality film footage and audiotapes of 911 communications with trapped victims. The BPAT team initially had difficulty in obtaining building blueprints and design drawings from either the City of New York, the Port Authority, the building owners, or the building designers due primarily to liability concerns on the part of the building owners and insurers. Belatedly, however, the team was provided access to these documents in early January.

ASCE has said that the BPAT study will not include an analysis of the evacuation or rescue procedures and may not be able to validate definitively any of a number of hypotheses regarding the collapse. But because of the confidentiality of the report, it is unclear whether the it will provide answers or simply lay out more questions. It is unknown, for example, to what degree the BPAT report will compare video evidence with that collected from the steel beams from the floors that were hit by the planes.

As a result, independent researchers are unsure how they can contribute to the understanding of how the buildings fell without unnecessarily duplicating work. Others fear that the BPAT's silence on the scope of its report may allow critical aspects of the picture to be missed, and that, by the time the report is released and any such gaps are discovered, the trail of evidence that could provide answers may have grown cold.

The National Science Foundation

Researchers supported by the National Science Foundation are used to mobilizing rapidly after an earthquake and arriving on scene soon after the event to begin collecting data. Recognizing the similarities between the WTC disaster and earthquakes, NSF program managers awarded nearly $300,000 to experienced earthquake researchers, including engineers and social scientists, to begin an analysis of the 9/11 terrorist attacks within 72 hours of the events. In an effort to quickly deploy researchers to the site, awards were made through the Small Grants for Exploratory Research Program, a supplemental award program that enables NSF program managers to award additional support to currently-funded investigators through an abbreviated internal review process (see *Appendix B* for a list of awards).

The efforts of NSF-funded researchers were impeded by the same obstacles the BPAT team encountered: an inability to examine the steel, either removed from the site during the early search and rescue work or shipped to recycling plants, and the denial of access to building design, construction and maintenance documents. Interestingly, it was an NSF-funded researcher who ultimately negotiated the arrangements by which he and others investigating the disaster were provided access to the remaining pieces of steel at the recycling plant.

To date, the NSF-funded researchers continue to face problems. They continue to be denied access to important building diagrams and blueprints, and so are unable to complete their analyses or develop the computer models necessary to better understand the failure of the buildings structural elements. Perhaps more importantly, without these computer models, engineering researchers will be unable to develop effective mitigation strategies.

The National Institute of Standards and Technology

NISTs Building and Fire Research Laboratory carries out research in fire science, fire safety engineering, and structural, mechanical, and environmental engineering. It is the only federal laboratory dedicated to research on building design and fire safety. In the past, the lab has investigated several structural failures using authority Congress made explicit in 1985 (15 U.S.C. 282a). The goals of its previous investigations were to determine the probable technical causes of the failures, examine what lessons could be learned from those determinations, and help develop improved building codes, standards, and practices. The investigations also identified areas of research that needed further study.

Shortly after the attack, NIST appointed an employee of the Building and Fire Research Laboratory to serve on the 23-member BPAT team. While this partnership lent some of NIST's resources and expertise to the BPAT study, NIST did not immediately launch a formal investigation into the technical causes that led to the collapse of the World Trade Center buildings.

NIST believes that the World Trade Center collapse raises difficult and technical questions regarding building codes and standards, justifying the redirection of funds to its building and fire lab. For example, standards for concrete design, building loads, and structural integrity may need revision. In response, NIST has redirected $2 million of its fiscal year 2002 internal discretionary funds to the lab to supplement its current building engineering and standards work. NIST has also requested permission to reprogram from the rest of its laboratories another $2 million in fiscal year 2002 funds for these efforts. The reprogramming request is currently pending before the Office of Management and Budget and will ultimately need approval from Congress. NIST did not need Congressional review to redirect its discretionary funds. (See *Appendix C,* Building Design and Collapse Scenarios.)

In January, after a delay of three months since the terrorists' attacks, FEMA asked NIST to take over the next phase of the investigation of the collapse. Yet neither NIST nor FEMA has released details as to what that next phase would entail (other than the general outline NIST has provided below). In addition, the Administration has not yet indicated whether FEMA, NIST, or a supplemental funding request to Congress would provide funds for such an investigation, nor has it identified how much it would cost.

Administration officials and outside parties are weighing whether a formal arrangement should be made for NIST to serve as FEMA's research arm in the event of future catastrophic building failures. Currently, there is no formal relationship between the two agencies regarding these matters.

Based on some initial planning, NIST has preliminarily identified the following general areas for investigation:

- Determine technically, why and how the buildings collapsed (WTC 1 and 2, and possibly WTC 7);
- Investigate the technical aspects of fire protection, response, and evacuation, and occupant behavior and response;
- Determine whether state-of-the-art procedures were used in the design, construction, operation, and maintenance of the WTC building;
- Determine whether there are new technologies and procedures emerging that could be employed in the future to reduce the potential risks of collapse; and
- Identify building and fire codes, standards, and practices that warrant revision.

3. Questions

Please see *Appendix A* for copies of letters to witnesses and the questions each was asked to address in testimony at the hearing.

4. Witnesses

The following witnesses will address the Committee:

Mr. Robert Shea, Acting Administrator Federal Insurance and Mitigation Administration, and, Mr. Craig Wingo, Director of Division of Engineering Science and Technology, Federal Emergency Management Administration

Dr. W. Gene Corley, P.E., S.E., American Society of Civil Engineers, Chair of the Building Performance Assessment Team reviewing the WTC disaster

Professor Glenn Corbett, Assistant Professor of Fire Science at John Jay College, New York City

Dr. Abolhassan Astaneh-Asl, Professor, Department of Civil and Environmental Engineering, University of California, Berkeley

Dr. Arden Bemet, Director, National Institute of Standards and Technology

5. Additional Reading

Glanz, J. (2001, December 4). Wounded Buildings Offer Survival Lessons. *The New York Times,* p. F1

Glanz, J., & Lipton, E. (2001, December 25). A Nation Challenged: The Towers; Experts Urging Broader Inquiry in Towers' Fall. *The New York Times,* p. A1

Glanz, J., & Lipton, E. (2002, January 17). New Agency to Investigate the Collapse of Towers. *The New York Times,* p. B3

Glanz, J., & Lipton, E. (2002, February 2). At Scrapyards, as Search for Clues in the Towers' Collapse. *The New York Times,* p. B1

Appendix 2

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FRIDAY, MARCH 29, 2002

DC2101:
COMMITTEE HOUSE SCIENCE
DIANE HILL
2320 RAYBURN HOUSE OF
WASHINGTON 20515

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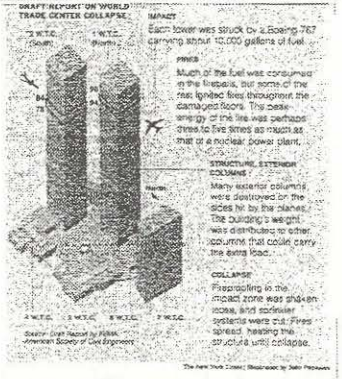


IMPACT
Each tower was struck by a Boeing 767 carrying about 10,000 gallons of fuel.

FIRES
Much of the fuel was consumed in the fireballs, but some of the rest ignited fires throughout the damaged floors. The peak energy of the fire was perhaps three to five times as much as that of a nuclear power plant.

STRUCTURE, EXTERIOR COLUMNS
Many exterior columns were destroyed on the sides hit by the planes. The building's weight was distributed to other columns that could carry the extra load.

COLLAPSE
Fireproofing in the impact zone was shaken loose, and sprinkler systems were cut. Fires spread, heating the structure until collapse.

Source: Draft Report by FEMA, American Society of Civil Engineers

The New York Times; Illustration by [illegible]

Towers Withstood Impact, But Fell to Fire, Report Says

By JAMES GLANZ and ERIC LIPTON

Fireproofing, sprinkler systems and the water supply for hoses all largely failed in the twin towers on Sept. 11 in the face of a blaze so intense that it drove temperatures as high as 2,000 degrees and generated heat equivalent to the energy output of a nuclear power plant, a federal report on how the towers fell has concluded.

The fire, combined with these failures, brought down the towers even after they had shown surprising and lifesaving resiliency to massive structural damage caused by the impact of two hijacked airliners, the report says.

The report's findings detail for the first time the horrific series of events that led to the collapse of two of the world's tallest buildings. They are contained in a draft of a report commissioned by the Federal Emergency Management Agency and the American Society of Civil Engineers.

The draft describes a structure that showed both remarkable strength and critical weaknesses. As was obvious to television viewers worldwide, the towers sustained the initial impact of the planes and were able to redistribute loads away from damaged columns so well that they could probably have remained standing indefinitely if not for the fires, an earthquake or a windstorm, the report said. Team members are still debating the delicate question of whether the tremendous fires could have brought the towers down on their own.

"The ability of the two towers to withstand aircraft impact without immediate collapse was a direct function of their design and construction characteristics, as was the vulnerability of the two towers to collapse as a result of the combined effects of the impacts and ensuing fires," the report concludes.

The report, a copy of which was obtained by The New York Times, is not due to be released officially until late April or early May. It provides documentary evidence that simultaneously supports and rejects many of the theories about what happened to the towers on Sept. 11.

What is already clear is that the jet fuel played a role somewhat different, though still critical, than some experts had speculated. After the planes slammed into the towers

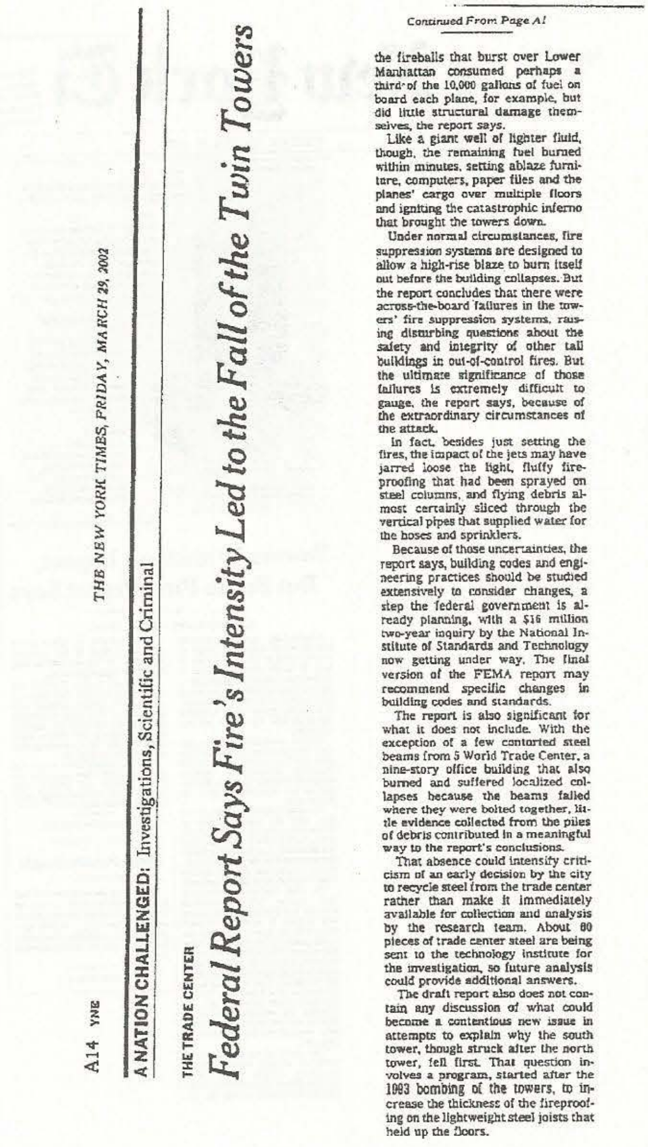
Continued on Page A14

Death Penalty Sought

The Justice Department said that it would seek the death penalty for Zacarias Moussaoui, the only person arrested in the Sept. 11 attacks. He is charged with conspiring with Osama bin Laden and the Qaeda terrorist network.

Article, Page A14.

Appendix 2



A14 YNE THE NEW YORK TIMES, FRIDAY, MARCH 29, 2002

A NATION CHALLENGED: Investigations, Scientific and Criminal

THE TRADE CENTER

Federal Report Says Fire's Intensity Led to the Fall of the Twin Towers

Continued From Page A1

the fireballs that burst over Lower Manhattan consumed perhaps a third of the 10,000 gallons of fuel on board each plane, for example, but did little structural damage themselves, the report says.

Like a giant well of lighter fluid, though, the remaining fuel burned within minutes, setting ablaze furniture, computers, paper files and the planes' cargo over multiple floors and igniting the catastrophic inferno that brought the towers down.

Under normal circumstances, fire suppression systems are designed to allow a high-rise blaze to burn itself out before the building collapses. But the report concludes that there were across-the-board failures in the towers' fire suppression systems, raising disturbing questions about the safety and integrity of other tall buildings in out-of-control fires. But the ultimate significance of those failures is extremely difficult to gauge, the report says, because of the extraordinary circumstances of the attack.

In fact, besides just setting the fires, the impact of the jets may have jarred loose the light, fluffy fireproofing that had been sprayed on steel columns, and flying debris almost certainly sliced through the vertical pipes that supplied water for the hoses and sprinklers.

Because of those uncertainties, the report says, building codes and engineering practices should be studied extensively to consider changes, a step the federal government is already planning, with a $16 million two-year inquiry by the National Institute of Standards and Technology now getting under way. The final version of the FEMA report may recommend specific changes in building codes and standards.

The report is also significant for what it does not include. With the exception of a few contorted steel beams from 5 World Trade Center, a nine-story office building that also burned and suffered localized collapses because the beams failed where they were bolted together, little evidence collected from the piles of debris contributed in a meaningful way to the report's conclusions.

That absence could intensify criticism of an early decision by the city to recycle steel from the trade center rather than make it immediately available for collection and analysis by the research team. About 80 pieces of trade center steel are being sent to the technology institute for the investigation, so future analysis could provide additional answers.

The draft report also does not contain any discussion of what could become a contentious new issue in attempts to explain why the south tower, though struck after the north tower, fell first. That question involves a program, started after the 1993 bombing of the towers, to increase the thickness of the fireproofing on the lightweight steel joists that held up the floors.

[illegible] in the north tower and 11 floors in the south tower had been upgraded, by increasing the thickness of the fireproofing from three-quarters of an inch to an inch and a half. As it happened, the planes hit floors in the north tower whose fireproofing thickness had already been increased, and floors in the south that had not been upgraded — with one exception, the 78th floor.

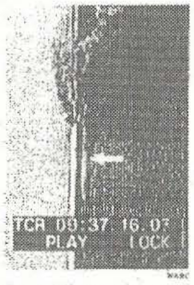
Team members are carefully debating what role that difference may have played in the length of time the towers stood after impact: 56 minutes, 10 seconds for the south tower and 102 minutes, 5 seconds for the north. But there are several other possible explanations. The plane that struck the south tower was moving at least 100 miles an hour faster than the other one, heightening the energy upon impact. And it hit 19 floors lower, resulting in far more weight from above bearing down on the damaged area.

Whatever its thickness, much of the fireproofing was probably dislodged by the impact of the planes, the investigators concluded. One official knowledgeable about the fireproofing said the wooly, mineral-based material could be brushed away with the wipe of a finger.

Stripped of its fireproofing, a steel column heats up much more quickly in a fire. The hotter the steel, the less it is able to support loads, as it eventually becomes as soft as licorice. Investigators believe that the structural steel was also greatly imperiled because the sprinklers and standpipes supplying water for firefighting were almost certainly disabled, their supply pipes cut by debris sent flying in the initial crash.

The sprinklers were installed by about 1990 and tanks were stored as high as the 110th floor of the buildings. Witnesses below the areas of impact, and therefore below the primary fires, described water cascading down the stairwells where pipes from those tanks ran. The hoses that firefighters carried on their backs up the same stairwells would therefore have been largely useless, since the standpipes used the same supplies.

The report cites the tight clustering of the exit stairways, three per tower, as a factor that may have made it easier to cause damage in all of them with one blow. These exit stairwells also had relatively lightweight gypsum board sheathing, providing little armor. Partly for these reasons, thousands of people above the floors of impact were trapped.



WABC

Arrow indicates molten metal, possibly aluminum from the airplane, coming from the south tower just minutes before it collapsed.

Most of the tenants in the floors below impact, to the credit of the building and the emergency lighting in the stairwells, escaped. More than 400 firefighters, police officers and other rescue personnel and dozens of tenants who stayed behind during the evacuation were also killed when the buildings finally collapsed. An estimated 2,830 people are considered dead or missing in the collapse.

Against the Manhattan skyline, the gleaming towers looked nearly identical, except for the television tower atop the north tower. But the inquiry found that the forces that toppled them had distinct differences.

Their basic structures before the attacks were extremely similar, even if they were not quite perfect twins. Each tower was supported against the downward force of gravity by a tightly arranged matrix of columns at its core and another palisade of columns, spaced just 40 inches apart, around its exterior.

The core and perimeter columns were connected by lightweight, weblike floor supports called trusses at each floor. The trusses held up corrugated metal decks on which the concrete floors were poured. The same trusses provided lateral support for all the vertical columns, preventing them from buckling under the tremendous force of gravity.

Wide plates called spandrels tied the exterior steel columns together, creating a rigid surface that could resist hurricane-force winds.

These structural elements would become fateful as the jets plowed into the north tower at 8:46 a.m. and the south tower at seconds before 9:03 a.m.

The report — assembled with data collected at ground zero, in scrapyards, in laboratories, by analyzing more than 100 hours of videotape and by talking to witnesses — turned up the greatest amount of detail on the south tower attack.

The United Airlines jet, its wings slightly canted, angled into the south facade of the south tower, slicing through about 30 of the 59 exterior columns on that face. The immediate damage, probably including unseen devastation to the steel core, stretched from the 78th to the 84th floors.

The impact of the plane, which had been traveling as fast as 586 miles an hour, was so great that it gathered office material like a snowplow and apparently forced it toward the northeast corner of the building. Parts of the plane came to rest there and others punctured the far wall, soaring as far as six blocks to the north before hitting the ground near the intersection of Murray and Church Streets.

A fuel-fed fireball emerged from three sides of the tower and consumed roughly one-third of the estimated 10,000 gallons on the plane. Some of the rest flowed down the face of the building and into elevator shafts and stairwells. What remained burned ferociously, setting acres of office space afire as well as the plane's cargo.

The incredible energy generated by this blaze was estimated peak to be three to five gigawatts at its peak. A typical nuclear power plant generates about one gigawatt. All of that energy was converted to deadly heat that began weakening the steel.

Remarkable strength, and critical weaknesses.

But the tower did not fall immediately. Preliminary calculations by the engineering team have revealed that the tight spandrel connections, built to resist the wind, gave the building a remarkable ability to redistribute loads from severed columns to those that remained intact.

This rearrangement was so efficient, the calculations show, that stresses on columns no more than 20 feet from the hole punched in the tower's face were barely higher than what they were before the impact.

But the fires continued to burn, black smoke poured from shattered windows on floor after floor, fresh oxygen sucked in from the gaping holes caused by the impacts. In the northeast corner of the south tower's 80th floor, where office furniture had been shoved by the plane, the fire burned so hot that a stream of molten metal began to pour over the side like a flaming waterfall.

The apparent source of this waterfall: molten aluminum from the jet's wings and fuselage, which had also piled up in that corner. Within minutes, portions of the 80th floor began to give way, as evidenced by horizontal lines of dust blowing out the side of the building. Seconds later, near the heavily damaged southeasterly portion of this same floor, close to where the aircraft had entered, exterior columns began to buckle.

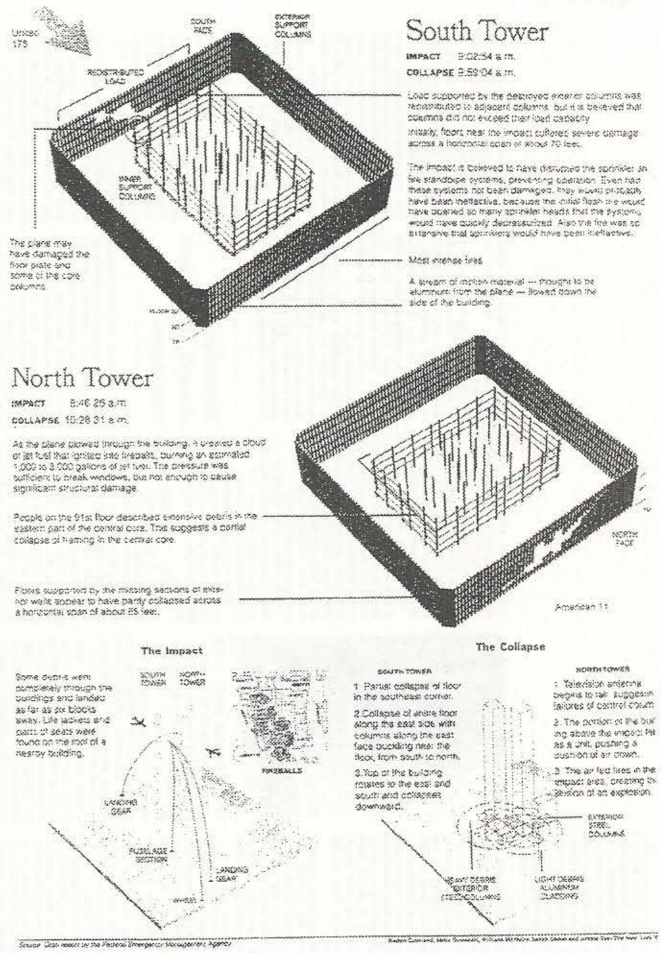
Fifty-six minutes and 10 seconds after it was hit, the top of the south tower tilted horribly, to the east and then to the south, and initiated the collapse of the entire tower, floor upon floor.

Unfolding at a slower pace, the disaster at the north tower will require study before it can be explained in such detail. The plane entered the north tower between the 94th and 98th floors, the report says, destroying about 35 columns on its north face and wreaking indeterminate but probably substantial damage to the core.

The building stood for more than an hour and a half. Videos of the north tower's collapse appear to show that its television antenna began to drop a fraction of a second before the rest of the building. The observations suggest that the building's steel core somehow gave way first, pulling down the rest of the tower with it.

For a few surreal moments, after the north tower had plummeted to the ground, a giant spearlike fragment of the facade remained standing, as if defiantly, looming above the lesser skyscrapers around it. Then the last shard of the tower fell, leaving behind only its arched, cathedral-like base and a narrow trail of smoke to trace its path to the ground.

Appendix 2


United 175
SOUTH FACE
EXTERIOR SUPPORT COLUMNS
REDISTRIBUTED LOAD
INNER SUPPORT COLUMNS
NORTH FACE
American 11
SOUTH TOWER
NORTH TOWER
FIREBALLS
LANDING GEAR
FUSELAGE SECTION
LANDING GEAR
WHEEL
EXTERIOR STEEL COLUMNS
HEAVY DEBRIS EXTERIOR STEEL COLUMNS
LIGHT DEBRIS ALUMINUM CLADDING

South Tower

IMPACT 9:02:54 a.m.

COLLAPSE 9:59:04 a.m.

Load supported by the destroyed exterior columns was redistributed to adjacent columns, but it is believed that columns did not exceed their load capacity.

Initially, floors near the impact suffered severe damage across a horizontal span of about 70 feet.

The impact is believed to have disrupted the sprinkler an fire standpipe systems, preventing operation. Even had these systems not been damaged, they would probably have been ineffective, because the initial flash fire would have opened so many sprinkler heads that the systems would have quickly depressurized. Also the fire was so extensive that sprinklers would have been ineffective.

Most intense fires

A stream of molten material — thought to be aluminum from the plane — flowed down the side of the building.

The plane may have damaged the floor plate and some of the core columns.

North Tower

IMPACT 8:46:26 a.m.

COLLAPSE 10:28:31 a.m.

As the plane plowed through the building, it created a cloud of jet fuel that ignited into fireballs, burning an estimated 1,000 to 3,000 gallons of jet fuel. The pressure was sufficient to break windows, but not enough to cause significant structural damage.

People on the 91st floor described extensive debris in the eastern part of the central core. This suggests a partial collapse of framing in the central core.

Floors supported by the missing sections of exterior walls appear to have partly collapsed across a horizontal span of about 85 feet.

The Impact

Some debris went completely through the buildings and landed as far as six blocks away. Life jackets and parts of seats were found on the roof of a nearby building.

The Collapse

SOUTH TOWER

1. Partial collapse of floor in the southeast corner.
2. Collapse of entire floor along the east side with columns along the east face buckling near the floor, from south to north.
3. Top of the building rotates to the east and south and collapses downward.

NORTH TOWER

1. Television antenna begins to fall, suggestin failures of central colum
2. The portion of the buil ing above the impact fel as a unit, pushing a cushion of air down.
3. The air fed fires in the impact area, creating th illusion of an explosion.

Source: Draft report by the Federal Emergency Management Agency

Chairman BOEHLERT. Good afternoon. I want to welcome everyone here today to our second hearing on the collapse of the World Trade Center. In many ways this hearing is a continuation of the discussions we began at our first hearing on March 6. And, indeed, we have the exact same panel of witnesses before us today as we did two months ago.

On March 6, we delved into the procedures that were followed to assess what had caused the towers to collapse in those indelible moments of September 11. We were not happy with what we learned. We found that the study of the collapse had been hampered by bureaucratic confusion, hesitation, and delay, by a lack of investigative tools, and by excessive restrictions on the flow of information.

But we also learned that despite these severe impediments, the team lead by the American Society of Civil Engineers, as well as other researchers, was able to draw some preliminary conclusions about the collapse, and the National Institute of Standards and Technology was willing to pick up where the ASCE team had left off, even though NIST officials couldn't tell us much, at that point, about exactly what that meant.

Today, we will pick up the story where we left off, focusing on three issues. First, the ASCE team will describe the conclusions of their study and it will become the subject of full-blown public deliberation for the first time. Second, NIST will tell us exactly what it intends to do in its follow-up investigation, for which the Administration has requested $16 million. And, third, we will release and open up the public discussion on legislation to ensure that the problems that hamstrung the ASCE study never, ever recur.

Let me first turn to the legislation, which I have drafted with my colleague, Mr. Weiner. The bill, known as the National Construction Safety Team Act, is designed to remedy each and every impediment that was encountered in the Trade Center investigation.

At the March 6 hearing, we uncovered four ways in which the status quo was unacceptable. First, no Federal agency was clearly charged with investigating building failures. The bill solves that problem by giving NIST clear responsibility to handle the investigations. Second, nothing ensured that investigations would begin quickly enough to preserve valuable evidence. The bill solves that problem by requiring NIST to act within 48 hours of a building failure.

Third, no Federal agency had the investigative authority it needed to ensure access to all needed information. The bill solves that problem by giving NIST clear authority to enter sites, access documents, test materials, and move evidence, as well as clear authority to issue subpoenas. Fourth, nothing ensured that the public was kept informed of the progress of the investigation. The bill solves that problem by requiring NIST to provide regular public briefings and to make public its findings and the materials that led to those findings.

We listened closely on March 6 and we have responded with a measure targeted precisely to remedy the issues that came to our attention. And we based the bill on a highly successful model, the National Transportation Safety Board, the Federal agency that investigates airline crashes.

We want to begin to get comments on the draft bill today, and we intend to introduce it, along with several colleagues on this Committee, and my colleagues from New York, Senators Clinton and Schumer, within the week. I expect our Committee to approve the bill by the end of the month and I would like to see it come to the House Floor as soon as possible.

While the bill is mostly prospective in its focus, all the investigative tools it would provide to NIST, including subpoena power, would be available to conduct the World Trade Center investigation.

But what will that investigation entail? That is the key question this Committee needs to pursue today with NIST. There is an almost unlimited universe of questions that NIST could address, but time and money are not unlimited. NIST needs to focus on those matters that are most likely to result in changed codes and practices, including evacuation and emergency response procedures in a wide variety of buildings.

The investigation can't be driven by mere curiosity or political pressures. And it can't be based on the assumption that unlimited dollars will flow for future research. It has to be driven by the desire to save the maximum number of lives in the future and to make the changes needed to save those lives as rapidly as possible. I hope that NIST will be able to assure us today that it is doing exactly that.

But regardless of the precise NIST agenda, the lab needs the $16 million that the Administration has requested for it in the supplemental appropriations bill that the House will consider later this month. The Administration is to be applauded for this request, although they have unfortunately complicated matters by asking that the money be provided to FEMA for transfer to NIST. We will work with the appropriators to get this money to NIST directly if possible; indirectly, if necessary. I don't really see why we have to go to FEMA, then to NIST. Why not directly to NIST?

So we still have plenty of questions as we pick up where we concluded on March 6. I want to assure the public in general, but especially the families of the victims, that this panel is committed to following this issue in the months and years ahead. We will not rest until we learn all we need to know to prevent future tragedies and until we implement what we have learned.

Let me conclude the same way I did on March 6. We are here because the only way to move forward is to try to understand what happened on a day that was so incomprehensible. With that, the Chair recognizes Mr. Hall.

[The prepared statement of Mr. Boehlert follows:]

PREPARED STATEMENT OF CHAIRMAN SHERWOOD BOEHLERT

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But what will that investigation entail? That's the key question this Committee needs to pursue today with NIST. There is an almost unlimited universe of questions that NIST could address, but time and money are not unlimited. NIST needs to focus on those matters that are most likely to result in changed codes and practices—including evacuation and emergency response procedures—in a wide variety of buildings.

The investigation can't be driven by mere curiosity or political pressures, and it can't be based on the assumption that unlimited dollars will flow for future research. It has to be driven by the desire to save the maximum number of lives in the future—and to making the changes needed to save those lives as rapidly as possible. I hope that NIST will be able to assure us today that it is doing exactly that.

But regardless of the precise NIST agenda, the lab needs the $16 million that the Administration has requested for it in the Supplemental Appropriations bill that the House will consider later this month. The Administration is to be applauded for this request, although they have, unfortunately, complicated matters by asking that the money be provided to FEMA for transfer to NIST. We will work with the appropriators to get this money to NIST—directly, if possible; indirectly, if necessary.

So we still have plenty of questions as we pick up where we concluded on March 6. I want to assure the public in general, but especially the families of the victims, that this panel is committed to following this issue in the months and years ahead. We will not rest until we learn all we need to know to prevent future tragedies and until we implement what we have learned.

Let me conclude the same way I did on March 6: We are here because the only way to move forward is to try to understand what happened on a day that was so incomprehensible.

Mr. HALL. Mr. Chairman, I certainly want to join you, as our chairman, in welcoming everyone to this Committee, and you and

Mr. Weiner, and others who have worked on your legislation. It is sensible, necessary, humanitarian legislation, as you alluded to 9/11, the day that terrorists declared war on this country with a dastardly act. We had loss of life there of people that may never even have enough of a body to have a decent funeral. Unbelievable tragedy that was forced and thrust upon us.

And I think, for those people—you know, like in World War I, World War II, when we lost a person, young or old—for those people who lost someone, that war never ends. It is there with them until they find closure. And they can only find closure through information and action. And you have to have the tools to make that happen.

Today, we are going to focus on the findings and recommendations of the Building Performance Assessment Team and the National Institute of Standards and Technology's follow-on legislation and their research agenda, which is so necessary. And while I commend the team for their outstanding commitment and effort, their report highlights that a lot remains to be done, and that is where NIST comes in.

I hope to find out today whether they have the funding required to do a complete investigation. And I am certain that all the Committee members are united in ensuring that the required funds are provided to NIST.

And, finally, I want to welcome the members of the Skyscraper Safety Campaign and thank them for their contributions to the Committee's work. I want to, again, commend Chairman Boehlert for his leadership on this issue, his interest in this issue, his support of this issue, and his reaching out to work with all the members of the Committee.

And I want to yield to Representative Weiner who has a direct interest and thrust into this and to recognize Steve Israel and John Larson who had constituents that were killed on that dreadful day. But right now, I want to yield my time to Congressman Weiner, and I think he will handle the time and share some with Steve Israel. With that, Mr. Chairman, I thank you, and I thank all of you for what you are doing and what you will do.

[The prepared statement of Mr. Hall follows:]

PREPARED STATEMENT OF REPRESENTATIVE RALPH M. HALL

I want to join Chairman Boehlert in welcoming everyone to the Committee second hearing on the World Trade Center building investigation.

Today, we will focus on the findings and recommendations of the Building Performance Assessment Team and the National Institute of Standards and Technology's follow-on research agenda. While I commend the Team for their outstanding commitment and effort, their report highlights that much remains to be done—this is where NIST comes in. I hope to find out today whether they have the funding required to do a complete investigation. I am certain that all the Committee Members are united in ensuring that the required funds are provided to NIST.

Finally, I want to welcome members of the Skyscraper Safety Campaign and thank them for their contributions to the Committee's work.

I also want to commend Chairman Boehlert for his leadership on this issue and for reaching out to work with all the Members of the Committee.

Now, I yield the balance of my time to Rep. Weiner from New York City who has been working with Chairman Boehlert on legislation addressing building investigations.

Chairman BOEHLERT. Thank you very much. The gentleman recognizes the gentleman from New York, my colleague, Mr. Weiner, with whom we have worked hand-in-glove on a bipartisan basis to deal in a responsible and timely manner with this issue. Mr. Weiner.

Mr. WEINER. Thank you very much, Mr. Chairman. And I think that when this chapter is written, your leadership will be recognized in keeping this issue on the front burner and making sure we, in Congress, act to solve the problems. You know, no one would dispute that the attack on the World Trade Center could not have been anticipated. In many respects, we can only marvel at the skill of the designers of the Twin Towers and the workmanship of the thousands of nameless and faceless steel workers and laborers who constructed it.

Thousands of families will enjoy dinner together tonight because even under the most unimaginable circumstances, these proud buildings stood tall for more than an hour. But for the families of those lost, today's report offers little consolation and leaves many questions unanswered. And, sadly, because of the early missteps in the investigation, some of the most vexing questions may never be unraveled.

Thousands of tons of steel were carted away and recycled before any expert could examine what could have been telltale clues. Support trusses, fireproofing fragments, and even burned-out electrical switches that might have given scientists and engineers insight were lost forever even before an investigation was underway.

Ladies and gentlemen, this amounts to what is, indeed, a crime scene investigation. Yet, not only is there no smoking gun, there wasn't even a weapon found. There weren't even fingerprints taken, and, if truth be told, there wasn't even a detective assigned to the case until very late in the process.

The report is short on conclusions about design decisions that could have contributed to the deaths of so many firefighters and workers on the top floors. Should future buildings avoid the concentration of stairwells that were used in the Twin Towers? Was enough attention given to the communications infrastructure that failed once after the 1993 bombings of these same buildings, and tragically left hundreds of emergency workers climbing stairs up while officials on the ground knew that the buildings were about to come down?

Did the fireproofing separate from the steel because of the intense heat, or was it the design of this post-asbestos treatment that is in place in thousands of buildings and did this fail for other reasons?

We cannot bring back those lost on September 11. And today there are more than 25,000 mothers, fathers, aunts, uncles, fiancees, and loved ones who, thank God, escaped that day. But if we want to ensure that the legacy of this tragedy is that future building collapses are avoided or mitigated, then we need to do a better job of investigating the causes.

We pray that no other plane ever crashes into a tall building and we hope that an earthquake never rattles our skyscrapers. And we remain vigilant against the threat of a bomb in our city centers. But just as we are not satisfied to simply hope another plane doesn't crash, we need to create an investigative team, like the NTSB, to jump into action, to investigate building collapses, protect and preserve evidence, issue regular briefings, and reach conclusions that formalize standards for building design, egress, and emergency escape.

Chairman Boehlert, whose leadership I have already noted, and I are going to be introducing legislation that will create this new authority. I urge my colleague and the President to support this effort. And I yield what brief time I may have left to Mr. Israel for a few remarks, as well.

Chairman BOEHLERT. And you don't have any time left, but Mr. Israel will be recognized in a moment. We want to do it on a back and forth——

Mr. WEINER. Thank you, Mr. Chairman.

[The prepared statement of Mr. Weiner follows:]

PREPARED STATEMENT OF REPRESENTATIVE ANTHONY WEINER

No one would dispute that the attack on the World Trade Center could not have been anticipated. In many respects one can only marvel at the skill of the designers of the Twin Towers and the workmanship of the thousand nameless steelworkers and laborers.

Thousands of families will enjoy dinner together tonight because even under the most unimaginable of circumstances these proud buildings stood tall for more than an hour. But for the families of those who were lost, the report released today by FEMA offers little consolation and leaves many questions unanswered. And sadly, because of early missteps in the investigation, some of the most vexing questions may never be unraveled.

No one would dispute that the attack on the World Trade Center could not have been anticipated. In many respects one can only marvel at the skill of the designers of the Twin Towers and the workmanship of the thousands of nameless steelworkers and laborers.

Thousands of tons of steel were carted away and recycled before any expert could examine what could have been tell-tale clues. Support trusses, fireproofing fragments and even burnt out electrical switches that might have given scientists and engineers insight were lost forever—even before an investigation was underway.

The report is short on conclusions about design decisions that may have contributed to the deaths of so many firefighters and workers on the top floors. Should future buildings avoid the concentration of stairwells that were used in the Twin Towers? Was enough attention given to the communications infrastructure that failed in the 1993 bombing and tragically left hundreds of emergency workers climbing stairs while officials on the ground knew that the buildings were about to come down? Did the fireproofing separate from the steel beams because of the intense heat or is the design of this post-asbestos treatment—that is in place in thousands of buildings—fail for other reasons?

We cannot bring back those who were lost on September 11th. And today there are more than 25,000 mothers, fathers, aunts, uncles, fiancées and loved ones who we thank god escaped that day. But if we want to ensure that the legacy of this tragedy is that future building collapses are avoided or mitigated—we need to do a better job of investigating the causes.

We pray that no other plane ever crashes into a tall building. And we hope that an earthquake never rattles our nation's high rises. And we remain vigilant against the threat of a bomb in our city centers.

But we are not satisfied to simply hope that another plane crash doesn't occur. Rather, we need to create an investigative team like the NTSB to jump into action to investigate building collapses, protect and preserve evidence, issue regular briefings, and reach conclusions that formalize standards for building design, egress and emergency escape.

Chairman Boehlert, whose leadership on this issue has provided comfort to all the victims' families, and I will be introducing legislation to create this new authority.

I urge my colleagues and the President to support this effort.

Chairman BOEHLERT Follow usual procedure, to demonstrate to everyone how well we work together——

Mr. WEINER. Thank you, sir.

Chairman BOEHLERT On a bipartisan basis. The Chair recognizes Ms. Morella.

Ms. MORELLA. I thank you, Mr. Chairman. And I certainly thank you for calling this important hearing to follow up on our work of a couple of months ago. In March, we heard disturbing testimony on the investigation into the World Trade Center collapse—questions of jurisdiction, availability of evidence, and the scope of the inquiry surrounding the investigation leading to grave concerns from what we heard about the victims' groups and the public at large.

All the witnesses testified to the problems they encountered during the investigation and the need for further study into additional areas, new authority to investigate and deal with future catastrophes. And through your leadership, Mr. Chairman, the Science Committee has taken up these challenges. I believe that we have a strong blueprint for future action. I also thank Mr. Weiner for his work on this and Mr. Hall and others.

The attack on our Nation was truly unprecedented. The horror of the collapse of the Twin Towers will be etched on our minds for generations. And, yet, while we should never forget the rage and anger that we felt from this atrocity, we should also remember the heroic actions of everyday people.

And I know we have a number of people who are here today who are most affected by the tragedy of September 11. I want to offer my condolences for their loss, thank them for their sacrifices, applaud them for their perseverance. You are what makes this country great.

Today we are going to do three very important things. First, the release of the Building Performance Assessment Team report on the collapse of the World Trade Center. These men and women performed under difficult conditions without a clear mandate. Their investigation did not go smoothly.

Secondly, we will unveil NIST's plan for the future, acting on recommendations from BPAT, as well as a host of scientists, professional organizations, and other individuals. The National Institute of Standards and Technology has developed a comprehensive plan for an in-depth building and fire safety investigation into the collapse of the Twin Towers, as well as a multi-year research and development program to provide technical support to improve building and fire codes, standards, and practice. And, of course, NIST is the premier facility for research in building design and safety, and it is uniquely positioned to conduct this extensive investigation that would be necessary.

And, finally, the Science Committee has been hard at work providing the infrastructure and authority to conduct investigation into future events. And the draft today of the National Construction Safety Board Act to empower a team of investigators to conduct inquiries into building failures, in much the same way as the NTSB conducts investigation of airline crashes and other transportation disasters, is very important. The legislation specifically addresses the problems of authority and jurisdiction associated with the BPAT investigation and will provide a clear chain of command for future work.

Again, I commend you, Mr. Chairman, Mr. Weiner, and Mr. Hall. I am pleased to be an original cosponsor with you on that bill. I yield back, and thank you for the courtesy.

[The prepared statement of Ms. Morella follows:]

PREPARED STATEMENT OF REPRESENTATIVE CONSTANCE MORELLA

Mr. Chairman, thank you for calling this important hearing to follow up on our work of two months ago. In March, we heard disturbing testimony on the investigation into the World Trade Center collapse. Questions of jurisdiction, the availability of evidence, and the scope of the inquiry surrounded the investigation, leading to grave concerns among the victim's groups and the public at large. All the witnesses testified to the problems they encountered during the investigation, the need for further study into additional areas, and the need for new authority to investigate and deal with future catastrophes. Through your leadership, the Science committee has taken up these challenges and I believe we have a strong blueprint for future action.

The attack on our nation was truly unprecedented. The horror of the collapse of the twin towers will be etched on our minds for generations. And yet, while we should never forget the rage and anger we felt from this atrocity, we should also remember the heroic actions of everyday people. Men and women who lost their lives helping others for no other reason than because its their job. Men and women who came together to provide aid to the survivors and comfort to the grief stricken. America's worst moment may have come on a fateful morning in September, but some of its best have been coming for the past eight months. We have a number of people here today who were most affected by the tragedy of September and I want to offer my condolences for their loss, thank them for their sacrifices, and applaud them for their perseverance. You are what make this country great.

Today we do three very important things. First, we will herald the release of the Building Performance Assessment Team Report on the collapse of the World Trade Center. These men and women performed under difficult conditions and without a clear mandate. Their investigation did not go smoothly. Their was difficulty in accessing important records and material, information was not shared in a timely fashion, and the community was left out of the loop. Nevertheless, these problems were not because of the dedicated individuals conducting the study. They have worked hard and done the best with what they could do. What's more, they have been honest about their limitations and freely discussed the deficiencies in their report and called for further action. They have not swept the issues under the rug, but rather brought the problems out into the light. I realize that this small comfort to those suffering now, but it is imperative to avoid the same mistakes and the same suffering in the future. I commend them for their integrity and for their effort.

Second, we will unveil NIST's plan for the future. Acting on recommendations from BPAT as well as a host of scientists, professional organizations, and other individuals, the National Institute for Standards and Technology have developed a comprehensive plan for a in-depth building and fire safety investigation into the collapse of the Twin Towers as well as a multi-year research and development program to provide technical support to improve building and fire coeds, standards, and practices. NIST is the premier federal facility for research in building design and safety, and they are uniquely positioned to conduct the extensive investigations necessary to fully understand the World Trade Center collapse and prevent future disasters. With NIST at the helm, we are in very good hands.

Finally, the Science Committee has been hard at work providing the infrastructure and authority to conduct investigation into future events. Today we are releasing a draft of the "national Construction Safety Board Act" which will empower a team of investigators to conduct inquiries into building failures in much the same way the NTSB conducts investigation of airline crashes and other transportation disasters. The legislation specifically addresses the problems of authority and jurisdiction associated with the BPAT investigation and will provide a clear chain-of-command for future work.

I want to thank the witness for agreeing to appear before us today and am looking forward to your comments on NIST's plan as well as our proposed legislation.

Chairman BOEHLERT. Thank you so much, Ms. Morella. The Chair recognizes Mr. Israel.

Mr. ISRAEL. I thank the Chairman. I thank the Chairman for his customary bipartisanship and the wisdom with which he leads this Committee. Mr. Chairman, on September 11, Susan Clyne of

Lindenhurst went to her desk at the World Trade Center and lost her life. On September 11, Ray Downey of Deer Park went to try and save Ms. Clyne's life and lost his life as the third highest ranking member of the New York City Fire Department. I represent over 100 families who lost a loved one in the rubble of the World Trade Center.

This report is important to them, but while it may answer some questions about what happened that day, it leaves many other questions unanswered, particularly as it pertains to protecting against such a calamity in the future, especially when it comes to reviewing and changing our building codes.

Let me very briefly share just three sentences from the report with my colleagues that I believe are fundamentally important. The report notes that during the course of this study, the question of whether building codes should be changed in some way to make future buildings more resistant to such attacks, was frequently explored.

It goes on to note that the BPS team felt that extensive technical policy and economic study of these concepts should be performed before any specific code change recommendations are developed. This report specifically recommends such additional studies. Future building code revisions may be considered after the technical details of the collapses and other building responses to damage are better understood.

The report raises the question of how building codes should be changed to withstand the potential of future attacks, but it fails to really answer it. It calls for additional studies. And the problem, as I see it, is that some at NIST are recommending a $40 million study to truly embrace all of the building code issues, while others are recommending 1/10 of that. We can't shortchange every American who enters any American building in the future.

The Chairman is absolutely correct. Time and money are not limitless, but I believe that we have a fundamental obligation to learn from the past, to act on the future, and to invest in the basic premise of keeping Susan Clyne and Ray Downey, and every American who goes to their jobs in a tall building and sits behind their desks, free from this kind of attack in the future. I thank the Chairman and I thank my colleague, Mr. Weiner, and I look forward to continuing to work with them.

Chairman BOEHLERT. Thank you very, Mr. Israel. And the Chair will now recognize—and this the final recognition—Mr. Grucci. The Chair is recognizing those members of the panel that have been most active in working on this legislation and have been most directly affected because of constituencies. All members will have an opportunity to have their full statements appear in the record at this juncture. With that, the Chair recognizes Mr. Grucci, my colleague from New York.

Mr. GRUCCI. Thank you, Mr. Chairman. And I, too, want to congratulate you for your leadership on this issue, a very, very important issue, and my colleagues who have been working on this. Mr. Weiner, thank you for your leadership.

I, too, represent a district where a number of families have lost loved ones, whether they were working in the building or working to try and save people in the building. And it has been a very difficult and a very tough time for all of America and certainly for those families who have to now live this horrible, horrible experience throughout the rest of their days.

And to that end, the Nation has embraced New York in the greatest time of its need. As we continue to come to grips with the horrific terrorist attacks of September 11, the tragedy that took place at the World Trade Center was one of unimaginable magnitude. We saw the best of New York: communities joining together to aid their families, friends, and people who they have never met. Now, more than 8 months after that fateful morning, we continue to work together to see that a tragedy like this never happens again.

I am proud to be an active part of the Science Committee's investigation into this tragedy and look forward to hearing from our witnesses. I have placed my full support behind this legislation and I am working closely with Chairman Boehlert to make this bill the best it can possibly be. I am interested in learning the findings and the recommendations from NIST and the Building Performance Assessment Team, and I am committed to working with the Committee and the investigative team to complete a full investigation. I wish to recognize the presence of the many victims' families and applaud you for your dedication and I stand with you in this very difficult time.

Thank you, Mr. Chairman, for your leadership on this hearing and in the investigation. And from one New Yorker to another, thank you for your commitment to these families and to all those who have lost loved ones in this tragic event, this terrorist attack of September the 11th. And we will work until we find a way to ensure that people will be safe when they go to work. Thank you, Mr. Chairman. And I yield back the remainder of my time.

[The prepared statement of Mr. Grucci follows:]

PREPARED STATEMENT OF REPRESENTATIVE FELIX J. GRUCCI, JR.

Thank you Mr. Chairman.

The Nation has embraced New York in its greatest time of need, as we continue to come to grips with the horrific terrorist attacks of September 11.

The tragedy that took place at the World Trade Center was one of unimaginable magnitude. We saw the best of New York, communities joining together to aid their families, friends, and even complete strangers. Now, more than eight months after that fateful morning, we continue to work together to see that a tragedy like this one may never happen again.

I am proud to be an active part of the Science Committee's investigation into this tragedy and look forward to hearing from our witnesses. I have placed my full support behind the legislation and am working closely with Chairman Boehlert to make this the best bill possible. I am interested to learn the findings and recommendations from NIST and the Building Performance Assessment Team, and am committed to working with the Committee and investigative teams to complete a full investigation. I wish to recognize the presence of many of the victim's families and applaud you for your dedication and stand with you in this difficult time.

Thank you Mr. Chairman for your leadership on this hearing and investigation, and from one New Yorker to another, thank you for your commitment to New York.

I yield back the balance of my time.

[The prepared statement of Ms. Lee follows:]

PREPARED STATEMENT OF REPRESENTATIVE SHEILA JACKSON LEE

Mr. Speaker,

I would like to thank you for holding this hearing today and I would also like to thank the distinguished group of witnesses who have taken the time to join us again and share their knowledge on this issue.

The National Institute of Science and Technology (NIST) has recently informed the Committee of prepared initial plans for its own investigation, and the Administration has requested supplemental funding of $16 million to pay for NIST's investigation. However, I am concerned about additional issues which have arisen in recent weeks, such as the point that the FEMA designated building performance assessment (BPAT) report is a start but more work needs to be done with an expanded expert-driven committee.

The main reason for the numerous hearings the Committee has held and the time and effort invested into this topic is prevention and readiness for a possible future attack. Therefore, I am especially curious as to the circumstances under which FEMA would ask the NIST for assistance.

Secondly, it is unclear whether the second phase of NIST's follow-up plans—a 3-year research effort to determine whether and how changes in building codes should be made—will receive the commitment for funding it requires. In addition to conducting a $16 million follow-up investigation to collect more data regarding the Trade Center disaster, NIST also proposes to conduct longer-term research on issues identified by the building performance assessment team (BPAT) report. For example, NIST plans to develop computer models of the collapse and conduct experiments to better understand the effect of fire on steel connections in buildings.

NIST estimates, however, that the total cost of the program will be approximately $40 million over the next three years. While NIST has said that some funds may be contributed by private sources, it is unclear if any such commitments have been made.

If adequate funding for NIST's research efforts are not secured it is unclear how NIST will use the information it collects in its investigation to improve standards, practices and codes for buildings and fire.

I hope that some of the distinguished guests here today will able to clear up some of the vagueness that surrounds this issue, which is obviously of great importance to this committee.

Thank you.

Chairman BOEHLERT. Thank you very much. And I want to thank all of my colleagues for their very thoughtful presentations. Now, we are going to go forward with our panel of expert witnesses and, gentlemen, I thank you all for the dedication you have evidenced to this important task. You were all here on March 6. We listened. We learned. We are here to listen again and we are here to learn, but we are also here to act.

What we are going to do is give the panel varying time allocations. Dr. Corley, you are going to get the most time because you are going to talk about the study, and we will give you 15 minutes. And the Chair will not be arbitrary, but would ask you to try to summarize in 15 minutes. Dr. Bement, we will have you talk about where we are going from here with NIST, and we will give you 10 to 15. And then, Mr. Shea, and, Professor Corbett, we would ask that you try to have five minutes or so, but if you need more—this is too darn important to have some clock ticking away, saying, well, you have got to stop and summarize in 60 seconds or less. So we are going to give you the time you need, but we want to be mindful of the interest of the panel and getting some questions in.

And then, finally, Dr. Barnett, you are here as a resource to Dr. Corley, as I understand it. And you are a two-tag team. Is that how it is going to work? You determine how that will work. Mr. Shea, you are up first. Mr. Robert Shea, Acting Administrator, Federal Insurance and Mitigation Administration.

STATEMENT OF MR. ROBERT F. SHEA, ACTING ADMINISTRATOR, FEDERAL INSURANCE AND MITIGATION ADMINISTRATION, FEDERAL EMERGENCY MANAGEMENT AGENCY

Mr. SHEA. Thank you, Mr. Chairman, Members of the Committee. I respectfully request that my written testimony be entered into the record and that I be allowed to make a very brief opening statement.

Chairman BOEHLERT. Without objection, all the formal presentations will be in the record at this juncture in their entirety, and we appreciate your willingness to try to summarize and highlight.

Mr. SHEA. Thank you, Mr. Chairman. Today, we will examine the reasons why the World Trade Center collapsed as a result of the horrendous terrorist act. However, nothing that we do today will explain the human tragedy. It is that tragedy that brings us together today. Dr. Corley and his team are to be commended. Never have we dealt with a report of this complexity in this length of time. All of us were spurred by the events of September 11. After today, as been noted by the Chairman and others, much remains to be done, and particularly, I think, by Dr. Bement and his team at the National Institute of Standards and Technology. FEMA stands ready to assist at this point.

Nonetheless, we remain compelled by the human tragedy. And I want to thank the Committee, and particularly the families and the heroes and victims, for their patience and their understanding. Thank you, Mr. Chairman.

[The prepared statement of Mr. Shea follows:]

PREPARED STATEMENT OF ROBERT F. SHEA

Mr. Chairman, Members of the Committee, I appreciate the opportunity to appear before you today to discuss the Federal Emergency Management Agency's Building Performance Assessment Team. My name is Robert Shea, Acting Administrator for the Federal Insurance and Mitigation Administration, and I am here representing Joe Allbaugh, the Director of the Federal Emergency Management Agency (FEMA).

At the Committee's March 6th hearing, FEMA described the engineering study of the tragic collapse of the World Trade Center, which was caused by terrorists inflicting a direct attack on America. This study and report have been completed with unprecedented speed. All our previous work pales by comparison. I am pleased that we are able to present this document to the Committee today. The Committee provided extremely helpful direction to FEMA during the last hearing that has assisted us in moving forward to complete this initial report.

To achieve a broader review of the FEMA/ASCE World Trade Center study, FEMA asked the witnesses from the last hearing to review and provide comments on the report. Additionally, FEMA asked the National Science Foundation (NSF) to identify reviewers to evaluate and comment on the report. ASCE arranged for additional outside reviewers from various technical committees from within ASCE. I invited Chief Ed Stinnette, Chief of the Fairfax County Fire Department in Virginia, to participate in this outside review of the report, as well. The BPAT team considered every single comment and made modifications to the report, where appropriate. FEMA is genuinely appreciative of the contributions from these reviewers because this process has helped to ensure that this report is well rounded and will serve as a stable foundation upon which the National Institute of Standards and Technology (NIST) can embark on its long-term investigation.

Chief Stinnette provided particularly valuable insights, showing the importance of the fire service, including the United States Fire Administration, in the future work that the NIST has proposed. The National Science Foundation Review process for the report was extremely productive and well supported by Dr. Rita Colwell and Dr. Priscilla Nelson at NSF. We will take advantage of this review process for any similar future efforts that we are engaged in.

All of the reviewers were given the option of addressing a letter to me on major public policy issues to be included as an Appendix to the report. No reviewer accepted this offer.

FEMA has signed a Memorandum of Understanding (MOU) with NIST that will help to guide our future collaborations on similar types of studies, and we are committed to work with NIST and NSF to identify how we can. For these types of extreme events, whether natural or man-made, the MOU will serve as a road map to establish protocols for future collaboration of our two agencies under our respective authorities.

Dr. Gene Corley, the BPAT Team leader, is to be commended. He and the Team have done remarkable work. They have done a great service for this country. I would also like to recognize the very real contribution that the prime contractor has made, Greenhorne and Omara. The report would not have been available today without their support.

Finally, I want to thank the Committee and, particularly, the families for their patience.

I would now be pleased to answer any questions that the Committee may have.

BIOGRAPHY FOR ROBERT F. SHEA

Robert F. Shea was appointed Acting Administrator of the Federal Insurance and Mitigation Administration in August 2001 after an agency-wide reorganization. Previously, Mr. Shea was deputy administrator for mitigation in FEMA. In his acting capacity, Mr. Shea is responsible for overseeing the insurance and risk reduction activities of FEMA, including educating residents and state and local official about the importance of risk reduction activities. Mr. Shea also coordinates efforts to educate the public on the importance of insuring property against flood damage.

Previously, Mr. Shea served as the Division Director for the Program Support Division within FEMA's then-Mitigation Directorate. In that capacity, he provided executive direction to the Hazard Mitigation Planning Program, the Hazard Mitigation Grant Program and the Flood Mitigation Assistance Program.

Mr. Shea has spent 25 years in emergency management in FEMA, serving in various capacities, including chief of the Coordination Office of the former State and Local Program and Support Directorate and chief of the Program Development Division in the former Office of Earthquakes and Natural Hazards.

A native of Atlanta, Ga., Mr. Shea earned Bachelor's and Masters's degrees in English Literature from The Catholic University of America.

Chairman BOEHLERT. Thank you very much. Dr. Gene Corley, American Society of Civil Engineers. Dr. Corley is the Chair of the Building Performance Assessment Team, which has reviewed the WTC disaster. And let me say, the Nation owes a debt of gratitude to you and your outstanding organization, the American Society of Civil Engineers. We appreciate very much what you are doing. The task isn't over, as you well know. And with that, Dr. Corley, the floor is yours.

STATEMENT OF DR. W. GENE CORLEY, P.E., S.E., CTL ENGINEERING, CHICAGO, ILLINOIS, ON BEHALF OF THE AMERICAN SOCIETY OF CIVIL ENGINEERS, CHAIR OF BUILDING PERFORMANCE ASSESSMENT TEAM REVIEWING THE WORLD TRADE CENTER DISASTER; ACCOMPANIED BY DR. JONATHAN BARNETT

Dr. CORLEY. Thank you, Mr. Chairman. If you will permit me, I do have some illustrations that will be shown as I speak. I would like to start by just commenting that during our work on the team the tragedy that occurred was uppermost in our mind, and continually we recognize the losses of those who were in the buildings and the loss forever to those who remain behind. The work that we did was intended to help those in the future.

Over the next few minutes, I will first describe briefly the composition of the team and give a short illustration of some of the tools we used, but I will concentrate mostly on the important findings that we have and the recommendations we have for the NIST study.

Our team was made up of approximately 25 people. Among these members of the team were structural engineers, designers, analysts, professors, my colleague, Dr. Jonathan Barnett, and we also had firemen on the team, investigators, a wide range of expertise to do this work.

The scope of the investigation was not to come to final conclusions. We simply didn't have the resources or time to do that. But, first, collect and preserve data, then do preliminary analyses within the time limits that we had, make recommendations for additional work where appropriate, and, for those items that we could come to a conclusion on, make recommendations that might improve the performance of buildings in the future.

There were several buildings that were very much of importance to us. Obviously, Buildings 1 and 2, the two towers, were high on our list of buildings to study. Building 3, the Marriott Hotel, which was crushed by the falling debris, was on our list. But we had others—Buildings 4, 5 and 6, that were around the base of the towers, were still partially standing and provided us with insight as to the performance of buildings in fire. Building 7, which was across the street from the main towers, also collapsed and provided us with the first example that we recognized of a building collapsing as a result of fire. Bankers Trust was another building of importance because it stood up and did not collapse as a result of the attack.

To orient everyone just briefly, the four buildings that collapsed are shown in the center of this slide. They are the four buildings that are not colored. In addition to those, the three red buildings around the base of the towers are Buildings 4, 5, and 6. Bankers Trust is across the street at the bottom of the slide. We also investigated and commented on all of the buildings in blue and yellow on this slide.

To briefly mention how we did some of our work—this is a view looking down upon the World Trade Center site and it shows one of the aircraft as it approached. In this case, it was the aircraft that crashed into Tower 1. We were able to get the information on size of that aircraft. And we also, from the photographs that we had, were able to determine the angle at which that plane hit the building.

Using this information, we were able to go from photographs, such as this, that we enhanced with the help of others, so that we could see the damage to the building. And we were able to come up with information as shown here. This shows the north face of the north tower, Tower 1, and shows where the aircraft plunged into the building, and which of the columns were destroyed or damaged as a result of the crash into the building.

Based upon all the information we were able to gather, we have a number of findings and observations. First of all, the tower sequence of collapse. Clearly, the impact of the aircraft was not enough to bring down either of the two towers. It required a second major event, an event that could have been wind, earthquake, or any of the normal things that we expect will affect buildings. In this case, the second event was the fire.

The buildings survived for the time that they did—one for almost an hour, the other for substantially more than an hour—because of several items. First of all, there were a large number of columns so that there was a way to transfer the load into other parts of the building after substantial portions of the building were removed by the crash. Then, those columns that were there before the crash had over capacity, so that when the load was transferred to them, they still had enough reserve capacity to carry the additional load.

In Buildings 1 and 2, the impact, we found, did dislodge some of the fireproofing. It also damaged the stair enclosures, thereby blocking five of the six stairwells in the buildings. There were three in each building. We believe all of the stairwells were blocked by the impact in Tower 1 and two of the three were blocked in Tower 2. We know that four people did escape from above the crash level in Building 2 and, therefore, that was the evidence that one stairway was passable, though not in good condition. The collapse occurred from the fire after the very horrendous damage that was done by the aircraft crashing into the two towers.

We have several lessons learned from this. These lessons can be used to improve future construction. For those buildings that are identified as potential targets for terrorists, we have found a need for the redundancy like we saw in these buildings. We need a way to transfer the load into other parts of the building so that they don't collapse immediately. We also need robustness—that is, the over-strength in parts of the building, so when the load is transferred to them, they have the capacity to take it.

We also need to consider the fire resistance as it is related to the importance of the member that is being protected from the fire. Some parts of the building are more important than other parts and, therefore, need to have different fire resistance.

For the fireproofing itself, we learned several lessons. Again, these can be applied immediately to those buildings that are potential targets for terrorist attack. For one thing, we found that we need the fireproofing to stick better to the steel. It needs to stick not only under the impact that we might expect in a building that is attacked by terrorists, but also under the deformations that may occur in the parts of the building as the fire heats them up and weakens them. It needs to be effective after the attack.

We have learned lessons about the fire protection for, again, buildings that are possibly terrorist targets. The sprinkler system, the water supply needs to be reliable, and we need redundancy in the system so that if we lose the water from one source, we have another way to supply water. We obviously saw in these buildings that the sprinklers did not work, and that means that we have a reduction in the protection that we have for the buildings.

We learned lessons about exiting the buildings. Again, for buildings that might be the target of terrorists, we need redundancy in the exits. We need more than one way of getting out of a building. We need those exits to be strong enough that they can take the impact that can occur as a result of these attacks, and we need a separation of the exits, one from another, so that if an attack occurs in one part of the building, there is a better chance that the other part of the building, which was not hurt as badly, will have an exit that is operational. Finally, we need impact resistance in the exits.

For connections—we have learned several things about connections, and this can apply to buildings more than just those that might be terrorist targets. First of all, we need to have connections fire-rated. And when I talk about connections, I am talking about the way in which we attach beams to columns and make attachments within the length of a beam, that sort of thing.

In addition, we need test data. At the moment we do not have the test data to tell us what to do to get the ratings that are appropriate. We also need further analysis to see what the effect is of the types of changes that we might make in future building codes.

One of the major things that we have concluded is that there are several areas that we need additional work on. We did not anticipate that we would answer all of the questions with this study. We did always anticipate that we would point the direction to those things that need further work. We need to complete the analyses that we started in our part of the study.

We also need to develop fire test information. We need to physically test connections under the conditions of fire so that we can determine how to recommend the fire protection of connections.

Another thing is, we need to complete the study of Tower 7. Again, this was the first building we recognized that collapsed as a result of fire alone, without known severe physical damage to the building besides the fire.

Another area which we did not get into in any depth in this study is the human factors: how people reacted to the events, how they exited the buildings, what needs to be done to make it more certain that they will make the right choice in how they try to exit the buildings. That is a large area that does need additional study. And there are a number of other items in our report that we identify as having specific research needs.

In summary, the towers survived the impacts. It was the fire, in addition to this very severe impact, that finally brought the towers down. They would have stood there indefinitely waiting for the next big event if the fire had not been occurring virtually simultaneously with the effects of the impact.

Redundancy and robustness worked in the towers and it also worked in adjacent buildings, such as Bankers Trust. Major supports in a building need special consideration for fire protection. We believe that it was one of the major supports in Building 7 that started to collapse first and allow the entire building to come down. Fire resistance of connections is an important consideration that is not thoroughly addressed at the moment in the building codes and this needs to be changed.

We need to relate the fireproofing to the fire load. If the loads are increased in an area, then we need to apply appropriate fireproofing in that area. And, finally, egress or exiting with impact needs to be reviewed. The exit ways, such as stairwells, need to be able to survive the impacts that might occur in those buildings that might be subject to terrorist attacks. Thank you, Mr. Chairman.

[The prepared statement of Dr. Corley follows:]

PREPARED STATEMENT OF W. GENE CORLEY

Following the September 11, 2001, attacks on New York City's World Trade Center, the Federal Emergency Management Agency (FEMA) and the Structural Engineering Institute of the American Society of Civil Engineers (SEI/ASCE), in association with New York City and several other federal agencies and professional organizations, deployed a team of civil, structural, and fire protection engineers to study the performance of buildings at the World Trade Center (WTC) site.

Founded in 1852, ASCE represents more than 125,000 civil engineers worldwide and is the country's oldest national engineering society. ASCE members represent the profession most responsible for the nation's built environment. Our members work in consulting, contracting, industry, government and academia. In addition to developing guideline documents, state-of-the-art reports, and a multitude of different journals, ASCE, an American National Standards Institute (ANSI) approved standards developer, establishes standards of practice such as the document known as ASCE 7 which provides minimum design loads for buildings and other structures. ASCE 7 is used internationally and is referenced in all of our nation's major model building codes.

The events of following the attacks in New York City were among the worst building disasters and resulted in the largest loss of life from any single building event in the United States. Of the 58,000 people estimated to be at the WTC Complex, over 3,000 lives were lost that day, including 343 emergency responders. Two commercial airliners were hijacked, and each was flown into one of the two 110-story towers. The structural damage sustained by each tower from the impact, combined with the ensuing fires, resulted in the total collapse of each building. As the towers collapsed, massive debris clouds, consisting of crushed and broken building components, fell onto and blew into surrounding structures, causing extensive collateral damage and, in some cases, igniting additional fires and causing additional collapses. In total, 10 major buildings experienced partial or total collapse and 30 million square feet of commercial office space was removed from service, of which 12 million belonged to the WTC complex.

Scope of the study

The purpose of the FEMA/ASCE was to see what could be learned to make buildings safer in the future. Building performance studies are often done when there is major structural damage due to events such as earthquakes or blasts. A better understanding of how building respond to extreme forces can help us design safer structures in the future.

Specifically, the scope of the FEMA/ASCE study was to:

- review damage caused by the attack;
- assess how each building performed under the attack;
- determine how each building collapsed;
- collect and preserve data that may aid in future studies; and
- offer guidelines for additional study.

The team examined:

- The immediate effects of the aircraft impact on each tower;
- The spread of the fire following the crashes;
- The reduction in structural strength caused by the fires;
- The chain of events that led to the collapse of the towers; and
- How falling debris and the effects of the fires impacted the other buildings at the World Trade Center complex.

The team recommendations are presented for more detailed engineering studies, to complete the assessments and produce improved guidance and tools for building design and performance evaluation.

World Trade Center 1 and World Trade Center 2

As each tower was struck, extensive structural damage, including localized collapse, occurred at the several floor levels directly impacted by the aircraft. Despite this massive localized damage, each structure remained standing. However, as each aircraft impacted a building, jet fuel on board ignited. Part of this fuel immediately burned off in the large fireballs that erupted at the impact floors. Remaining fuel flowed across the floors and down elevator and utility shafts, igniting intense fires throughout upper portions of the buildings. As these fires spread, they further weakened the steel-framed structures, eventually triggering total collapse.

The collapse of the twin towers astonished most observers, including knowledgeable structural engineers, and, in the immediate aftermath, a wide range of explanations were offered in an attempt to help the public understand these tragic and unthinkable events. However, the collapse of these symbolic buildings entailed a complex series of events that were not identical for each tower. To determine the sequence of events, likely root causes, and methods or technologies that may improve or mitigate the building performance observed, FEMA and ASCE formed a Building Performance Study (BPS) Team consisting of specialists in tall building design, steel and connection technology, fire and blast engineering, and structural investigation and analysis.

The SEI/ASCE team conducted field observations at the WTC site and steel salvage yards, removed and tested samples of the collapsed structures, viewed hundreds of images of video and still photography, conducted interviews with witnesses and persons involved in the design, construction, and maintenance of each of the affected buildings, reviewed available construction documents, and conducted preliminary analyses of the damage to the WTC towers.

With the information and time available, the sequence of events leading to the collapse of each tower could not be definitively determined. However, the following observations and findings were made:

- The structural damage sustained by each of the two buildings as a result of the terrorist attacks was massive. The fact that the structures were able to sustain this level of damage and remain standing for an extended period of time is remarkable and is the reason that most building occupants were able to evacuate safely. Events of this type, resulting in such substantial damage, are generally not considered in building design, and the fact that these structures were able to successfully withstand such damage is noteworthy.
- Preliminary analyses of the damaged structures, together with the fact the structures remained standing for an extended period of time, suggest that, absent other severe loading events, such as a windstorm or earthquake, the buildings could have remained standing in their damaged states until subjected to some significant additional load. However, the structures were subjected to a second, simultaneous severe loading event in the form of the fires caused by the aircraft impacts.
- The large quantity of jet fuel carried by each aircraft ignited upon impact into each building. A significant portion of this fuel was consumed immediately in the ensuing fireballs. The remaining fuel is believed either to have flowed down through the buildings or to have burned off within a few minutes of the aircraft impact. The heat produced by this burning jet fuel does not by itself appear to have been sufficient to initiate the structural collapses. However, as the burning jet fuel spread across several floors of the buildings, it ignited much of the buildings' contents, permitting fires to evolve across several floors of the buildings simultaneously. The heat output from these fires is estimated to have been comparable to the power produced by a large commercial generating station. Over a period of many minutes, this heat induced additional stresses into the damaged structural frames while simultaneously softening and weakening these frames. This additional loading and damage were sufficient to induce the collapse of both structures.
- The ability of the two towers to withstand aircraft impacts without immediate collapse was a direct function of their design and construction characteristics, as was the vulnerability of the two towers to collapse as a result of the combined effects of the impacts and ensuing fires. Many buildings with other design and construction characteristics would have been more vulnerable to collapse in these events than the two towers, and few may have been less vulnerable. It was not the purpose of this study to assess the code-conformance of the building design and construction, or to judge the adequacy of these features. However, during the course of this study, the structural and fire protection features of the building were examined. The study did not reveal any specific structural features that would be regarded as substandard, and, in fact, many structural and fire protection features of the design and construction were found to be superior to the minimum code requirements.

What caused the collapse of the towers?

Our analysis showed that the impact alone did not cause the collapse of the towers, but instead, left the towers vulnerable to collapse from any significant additional force, such as from high winds, an earthquake, or in the case of the Twin Towers, the fires that engulfed both buildings. Without that second event, the team believes the towers could have remained standing indefinitely.

Although steel is very strong, it loses some of its strength when heated. To prevent that loss of strength, structural steel is protected with fireproofing and sprinkler systems. In the towers, fires raged throughout several floors simultaneously, ignited by the jet fuel and fed by a mixture of paper and furniture. The impact dislodged some fireproofing on the structural beams and columns, which made them vulnerable to fire damage. With the sprinkler systems disabled, the fires raged uncontrollably, weakening the steel and leading to the collapse of the buildings.

Several building design features have been identified as key to the buildings' ability to remain standing as long as they did and to allow the evacuation of most building occupants. These included the following:

- robustness and redundancy of the steel framing system;
- presence of adequate egress stairways that were well marked and lighted; and
- the conscientious implementation of emergency exiting training programs for building tenants.

Similarly, several design features have been identified that may have played a role in allowing the buildings to collapse in the manner that they did and in the inability of victims at and above the impact floors to safely exit. These features should not be regarded either as design deficiencies or as features that should be prohibited in future building codes. Rather, these are features that should be subjected to more detailed evaluation, in order to understand their contribution to the performance of these buildings and how they may perform in other buildings. These include the following:

- the type of steel floor truss system present in these buildings and their structural robustness and redundancy when compared to other structural systems;
- use of impact-resistant enclosures around egress paths;
- resistance of passive fire protection to blasts and impacts in buildings designed to provide resistance to such hazards; and
- grouping emergency egress stairways in the central building core as opposed to dispersing them throughout the structure

Building Codes

During the course of this study, the question of whether building codes should be changed in some way to make future buildings more resistant to such attacks was frequently explored. Depending on the size of the aircraft, it may not be technically feasible to develop design provisions that would enable structures to be designed and constructed to resist the effects of impacts by rapidly moving aircraft, and the ensuing fires, without collapse. In addition, the cost of constructing such structures might be so large as to make this type of design intent practically infeasible.

Although the attacks on the World Trade Center are a reason to question design philosophies, the BPS Team believes there are insufficient data to determine whether there is a reasonable threat of attacks on specific buildings to recommend inclusion of such requirements in building codes. Some believe the likelihood of such attacks on any specific building is deemed sufficiently low to not be considered at all. However, individual building developers may wish to consider design provisions for improving redundancy and robustness for such unforeseen events, particularly for structures that, by nature of their design or occupancy, may be especially susceptible to such incidents. Although some conceptual changes to the building codes that could make buildings more resistant to fire or impact damage or more conducive to occupant egress were identified in the course of this study, the BPS Team felt that extensive technical, policy, and economic study of these concepts should be performed before any specific code change recommendations are developed. This report specifically recommends such additional studies. Future building codes revisions may be considered after the technical details of the collapses and other building responses to damage are better understood.

Surrounding Buildings

Several other buildings, including the Marriott Hotel (WTC 3), the South Plaza building (WTC 4), the U.S. Customs building (WTC 6), and the Winter Garden, experienced nearly total collapse as a result of the massive quantities of debris that fell on them when the two towers collapsed. The St. Nicholas Greek Orthodox Church just south of WTC 2 was completely destroyed by the debris that fell on it.

WTC 5, WTC 7, 90 West Street, 130 Cedar Street, Bankers Trust, the Verizon building, and World Financial Center 3 were impacted by large debris from the collapsing twin towers and suffered structural damage, but arrested collapse to localized areas. The performance of these buildings demonstrates the inherent ability of redundant steel-framed structures to withstand extensive damage from earthquakes, blasts, and other extreme events without progressive collapse.

The debris from the collapses of the WTC towers also initiated fires in surrounding buildings, including WTC 4, 5, 6, 7; 90 West Street; and 130 Cedar Street. Many of the buildings suffered severe fire damage but remained standing. However, two steel-framed structures experienced fire-induced collapse. WTC 7 collapsed completely after burning unchecked for approximately 7 hours, and a partial collapse occurred in an interior section of WTC 5. Studies of WTC 7 indicate that the collapse began in the lower stories, either through failure of major load transfer members located above an electrical substation structure or in columns in the stories above the transfer structure. The collapse of WTC 7 caused damage to the Verizon building and 30 West Broadway. The partial collapse of WTC 5 was not initiated by debris and is possibly a result of fire-induced connection failures. The collapse of these structures is particularly significant in that, prior to these events, no protected steel-frame structure, the most common form of large commercial construction in the United States, had ever experienced a fire-induced collapse. Thus, these events may highlight new building vulnerabilities, not previously believed to exist.

In the study of the WTC towers and the surrounding buildings that were subsequently damaged by falling debris and fire, several issues were found to be critical to the observed building performance in one or more buildings.

General Observations, Findings and Recommendations

These issues above fall into several broad topics that should be considered for buildings that are being evaluated or designed for extreme events. It may be that some of these issues should be considered for all buildings; however, additional studies are required before general recommendations, if any, can be made for all buildings. The issues identified from this study of damaged buildings in or near the WTC site have been summarized into the following points:

a. Structural framing systems need redundancy and/or robustness, so that alternative paths or additional capacity is available for transmitting loads when building damage occurs.

b. Fireproofing needs to adhere under impact and fire conditions that deform steel members, so that the coatings remain on the steel and provide the intended protection.

c. Connection performance under impact loads and during fire loads needs to be analytically understood and quantified for improved design capabilities and performance as critical components in structural frames.

d. Fire protection ratings that include the use of sprinklers in buildings require a reliable and redundant water supply. If the water supply is interrupted, the assumed fire protection is greatly reduced.

e. Egress systems currently in use should be evaluated for redundancy and robustness in providing egress when building damage occurs, including the issues of transfer floors, stair spacing and locations, and stairwell enclosure impact resistance.

f. Fire protection ratings and safety factors for structural transfer systems should be evaluated for their adequacy relative to the role of transfer systems in building stability.

What significant recommendations does the team make in its report?

What may be most important is that the BPS Team does not recommend any immediate changes to building codes. The Team believes that there are a number of areas that need further study, and that there are some things that building designers could do to improve safety for occupants in buildings that might be possible terrorist targets.

In general terms, the FEMA/ASCE report suggests that critical building components such as the structural frame, the sprinkler system or the exit stairwells be designed to be more redundant, more robust, or both. Redundancy means, for example, that if some structural columns were shattered, the building would be designed to transfer the weight to other columns. Robustness means making the builder stronger and better able to resist impact without collapse.

The team is also strongly urging additional study of the collapse of the buildings.

What key findings impact all existing buildings?

The team found that some connections between the structural steel beams failed in the fire. This was most apparent in the collapse of World Trade Center Building 5, where the fireproofing did not protect the connections, causing the structure to fail.

The team is calling for more research and analysis of the how the connections weakened and how best to strengthen their resistance to future fires. Typically, fire resistance tests are limited to steel members, not to the steel connections. Furthermore, fireproofing is sprayed on the connections the same way it is applied to the trusses, though the steel in the trusses and joints may be made of different alloys.

Specific Observations, Findings, and Recommendations

The following sections present observations, findings, and recommendations specifically made in each chapter of the FEMA/ASCE report, including the discussion of building codes and fire standards and the limited metallurgical examination of steel from the WTC towers and WTC 7.

Building Codes and Fire Standards

Observations and Findings

a. The decision to include aircraft impact as a design parameter for a building would clearly result in a major change in the design, livability, usability, and cost of buildings. In addition, reliably designing a building to survive the impact of the largest aircraft available now or in the future may not be possible. These types of loads and analyses are not suitable for inclusion in minimum loads required for design of all buildings. Just as the possibility of a Boeing 707 impact was a consideration in the original design of WTC 1 and WTC 2, there may be situations where it is desirable to evaluate building survival for impact of an airplane of a specific size traveling at a specific speed. Although there is limited public information available on this topic, interested building owners and design professionals would require further guidance for application to buildings.

b. The ASTM E119 Standard Fire Test was developed as a comparative test, not a predictive one. In effect, the Standard Fire Test is used to evaluate the relative performance (fire endurance) of different construction assemblies under controlled laboratory conditions, not to predict performance in real, uncontrolled fires.

World Trade Center 1 and World Trade Center 2

Observations and Findings

a. The structural damage sustained by each of the two buildings as aircraft impacted them during the attacks was massive. The fact that the structures were able to sustain this level of damage and remain standing for an extended period of time is remarkable and is the reason that most building occupants were able to evacuate safely. Events of this type, resulting in such substantial damage, are generally not considered in building design, and the ability of these structures to successfully withstand such damage is noteworthy.

b. Preliminary analyses of the damaged structures, together with the fact the structures remained standing for an extended period of time, suggest that absent other severe loading events, such as a windstorm or earthquake, the buildings could have remained standing in their damaged states until subjected to some significant additional load. However, the structures were subjected to a second, simultaneous severe loading event in the form of the fires caused by the aircraft impacts.

c. The large quantity of jet fuel carried by each aircraft ignited upon impact into each building. A significant portion of this fuel was consumed immediately in the ensuing fireballs. The remaining fuel is believed either to have flowed down through the buildings or to have burned off within a few minutes of the aircraft impact. The heat produced by this burning jet fuel does not by itself appear to have been sufficient to initiate the structural collapses. However, as the burning jet fuel spread across several floors of the buildings, it ignited much of the buildings' contents, permitting fires to evolve across several floors of the buildings simultaneously. The heat output from these fires is estimated to have been comparable to the power produced by a large commercial generating station. Over a period of many minutes, this heat induced additional stresses into the damaged structural frames while simultaneously softening and weakening these frames. This additional loading and damage were sufficient to induce the collapse of both structures.

d. Because the aircraft impacts into the two buildings are not believed to have been sufficient to cause collapse without the ensuing fires, an obvious question exists as to whether the fires alone, without the damage from the aircraft impact, would have been sufficient to cause such a collapse. The capabilities of the building fire protection systems make it extremely unlikely that such fires could develop without some unusual triggering event like the aircraft impact. For all other cases, the fire protection for the tower buildings provided in-depth protection. The first line of defense was the automatic sprinkler protection. The sprinkler system was intended to respond quickly and automatically to extinguish or confine a fire. The second line of defense consisted of the manual (FDNY/Port Authority Fire Brigade) firefighting capabilities, which were supported by the building standpipe system, emergency fire department use elevators, smoke control system, and other features. Manual suppression by FDNY was the principal fire protection mechanism that controlled a large fire that occurred in the buildings in 1975. Finally, the last line of defense was the structural fire resistance. The fire resistance capabilities would not be called upon unless both the automatic and manual suppression systems previously described failed. In the incident of September 11, not only did the aircraft impact disable the first two lines of defense, they also are believed to have dislodged fireproofing and imposed major additional stresses on the structural system.

e. Had some other event defeated both the automatic and manual suppression capabilities and a fire of major proportions occurred while the structural framing system and its fireproofing remained intact, the third line of defense, structural fireproofing, would have become critical. The thickness and quality of the fireproofing materials would have been key factors in the rate and extent of temperature rise in the floor trusses and other structural members. In the preparation of this report, there has not been sufficient analysis to predict the temperature and resulting change in strength of the individual structural members in order to approximate the overall response of the structure. Given the redundancy in the framing system and the capability of that system to redistribute load from a weakened member to other parts of the structural system, it is impossible without extensive modeling and other analysis to make a credible prediction of how the building would have responded to an extremely severe fire in a situation where there was no prior structural damage. Such simulations have not been performed within the scope of this study, but should be performed in the future.

f. Buildings are designed to withstand loading events that are deemed credible hazards and to protect the public safety in the event such credible hazards are experienced. Buildings are not designed to withstand any event that could ever conceivably occur, and any building can collapse if subjected to a sufficiently extreme loading event. Communities adopt building codes to help building designers and regulators determine those loading events that should be considered as credible hazards in the design process. These building codes are developed by the design and regulation communities themselves, through a voluntary committee consensus process. Prior to September 11, 2001, it was the consensus of these communities that aircraft impact was not a sufficiently credible hazard to warrant routine consideration in the design of buildings and, therefore, the building codes did not require that such events be considered in building design. Nevertheless, design of WTC 1 and WTC 2 did include at least some consideration of the probable response of the buildings to an aircraft impact, albeit a somewhat smaller and slower moving aircraft than those actually involved in the September 11 events. Building codes do regard fire as a credible hazard and include extensive requirements to control the spread of fire throughout buildings, to delay the onset of fire-induced structural collapse, and to facilitate the safe egress of building occupants in a fire event. For fire-protected steel-frame buildings, like WTC 1 and WTC 2, these code requirements had been deemed effective and, in fact, prior to September 11, there was no record of the fire-induced-collapse of such structures, despite some very large uncontrolled fires.

g. The ability of the two towers to withstand aircraft impacts without immediate collapse was a direct function of their design and construction characteristics, as was the vulnerability of the two towers to collapse as a result of the combined effects of the impacts and ensuing fires. Many buildings with other design and construction characteristics would have been more vulnerable to collapse in these events than the two towers, and few may have been less vulnerable. It was not the purpose of this study to assess the code-conformance of the building design and construction, or to judge the adequacy of these features. However, during the course of this study, the structural and fire protection features of the building were examined. The study did not reveal any specific structural features that would be regarded as substandard, and, in fact, many structural and fire protection features of the design and construction were found to be superior to the minimum code requirements.

h. Several building design features have been identified as key to the buildings' ability to remain standing as long as they did and to allow the evacuation of most building occupants. These include the following:

- robustness and redundancy of the steel framing system;

- presence of adequate egress stairways that were; and
- the conscientious implementation of emergency exiting training programs for building tenants.

i. Similarly, several design features have been identified that may have played a role in allowing the buildings to collapse in the manner that they did and in the inability of victims at and above the impact floors to safely exit. These features should not be regarded either as design deficiencies or as features that should be prohibited in future building codes. Rather, these are features that should be subjected to more detailed evaluation, in order to understand their contribution to the performance of these buildings and how they may perform in other buildings. These include the following:
    - the type of steel floor truss system present in these buildings and their structural robustness and redundancy when compared to other structural systems;
    - use of impact-resistant enclosures around egress paths;
    - resistance of passive fire protection to blasts and impacts in buildings designed to provide resistance to such hazards; and
    - grouping emergency egress stairways in the central building core, as opposed to dispersing them throughout the structure.

j. During the course of this study, the question of whether building codes should be changed in some way to make future buildings more resistant to such attacks was frequently explored. Depending on the size of the aircraft, it may not be technically feasible to develop design provisions that would enable structures to be designed and constructed to resist the effects of impacts by rapidly moving aircraft, and the ensuing fires, without collapse. In addition, the cost of constructing such structures might be so large as to make this type of design intent practically infeasible.

   Although the attacks on the World Trade Center are a reason to question design philosophies, the BPS Team believes there are insufficient data to determine whether there is a reasonable threat of attacks on specific buildings to recommend inclusion of such requirements in building codes. Some believe the likelihood of such attacks on any specific building is deemed sufficiently low to not be considered at all. However, individual building developers may wish to consider design provisions for improving redundancy and robustness for such unforeseen events, particularly for structures that, by nature of their design or occupancy, may be especially susceptible to such incidents. Although some conceptual changes to the building codes that could make buildings more resistant to fire or impact damage or more conducive to occupant egress were identified in the course of this study, the BPS Team felt that extensive technical, policy, and economic study of these concepts should be performed before any specific code change recommendations are developed. This report specifically recommends such additional studies. Future building codes revisions may be considered after the technical details of the collapses and other building responses to damage are better understood.

Recommendations

The scope of this study was not intended to include in-depth analysis of many issues that should be explored before final conclusions are reached. Additional studies of the performance of WTC 1 and WTC 2 during the events of September 11, 2001, and of related building performance issues should be conducted. These include the following:

a. During the course of this study, it was not possible to determine the condition of the interior structure of the two towers, after aircraft impact and before collapse. Detailed modeling of the aircraft impacts into the buildings should be conducted in order to provide understanding of the probable damage state immediately following the impacts.

b. Preliminary studies of the growth and heat flux produced by the fires were conducted. Although these studies provided useful insight into the buildings' behavior, they were not of sufficient detail to permit an understanding of the probable distribution of temperatures in the buildings at various stages of the event and the resulting stress state of the structures as the fires progressed. Detailed modeling of the fires should be continued and should be combined with structural modeling to develop specific failure modes likely to have occurred.

c. The floor framing system for the two towers was very complex and substantially more redundant than typical bar joist floor systems. Detailed modeling of these floor systems and their connections should be conducted to understand the effects of localized overloads and failures to determine ultimate failure modes. Other types of common building framing should also be examined for these effects.

d. The fire-performance of steel trusses with spray-applied fire protection, and with end restraint conditions similar to that present in the two towers, is not well understood, but is likely critical to the building collapse. Studies of the fire-performance of this structural system should be conducted.

e. Observations of the debris generated by the collapse and of damaged adjacent structures suggests that spray-applied fireproofing may be vulnerable to mechanical damage from blasts and impacts. This vulnerability is not well understood. Tests of these materials should be conducted to understand how well they withstand such mechanical damage and to determine whether it is appropriate and feasible to improve their resistance to such damage.

f. In the past, tall buildings have occasionally been damaged, typically by earthquakes, and experienced collapse within the damaged zones. Those structures were able to arrest collapse before they progressed to a state of total collapse. The two WTC towers were able to arrest collapse from the impact damage but not from the resulting fire when combined with the impact effects of the aircraft attack. Studies should be conducted to determine, given the great size and weight of the two towers, whether there are feasible design and construction features that would permit such buildings to arrest or limit a collapse, once it began.

World Trade Center 3

Observations

WTC 3 was subjected to extraordinary loading from the impact and weight of debris from the two adjacent 110-story towers. It is noteworthy that the building resisted both horizontal and vertical progressive collapse after the collapse of WTC 2. The overloaded portions were able to break away from the rest of the structure without pulling it down and the remaining structural system was able to remain stable and support the debris load. The structure was even capable of protecting occupants after the collapse of WTC 1.

Recommendations

WTC 3 should be studied further to understand how it resisted progressive collapse.

World Trade Center 7

Observations and Findings

a. This office building was built over an electrical substation and a power plant, comparable in size to that operated by a small commercial utility. It also had a significant amount of diesel oil storage and had a structural system with numerous horizontal transfers for gravity and lateral loads.

b. The loss of the east penthouse on the videotape records suggests that the collapse event was initiated by the loss of structural integrity in one of the transfer systems. Loss of structural integrity was likely a result of weakening caused by fires on the 5th to 7th floors. The specifics of the fires in WTC 7 and how they caused the building to collapse remain unknown at this time. Although the total diesel fuel on the premises contained massive potential energy, the best hypothesis has only a low probability of occurrence. Further research, investigation, and analyses are needed to resolve this issue.

c. The collapse of WTC 7 was different from that of WTC 1 and WTC 2. The towers showered debris in a wide radius as their external frames essentially "peeled" outward and fell from the top to the bottom. In contrast, the collapse of WTC 7 had a relatively small debris field because the facade came straight down, suggesting an internal collapse. Review of video footage indicates that the collapse began at the lower floors on the east side. Studies of WTC 7 indicate that the collapse began in the lower stories, either through failure of major load transfer members located above an electrical substation structure or in columns in the stories above the transfer structure. Loss of strength due to the transfer trusses could explain why the building imploded, with collapse initiating at an interior location. The collapse may have then spread to the west, causing interior members to continue collapsing. The building at this point may have had extensive interior structural failures that then led to the collapse of the overall building, including the cantilever transfer girders along the north elevation, the strong diaphragms at the 5th and 7th floors, and the seat connections between the interior beams and columns at the building perimeter.

Recommendations

The scope of this study was not intended to include in-depth analysis of issues. Certain issues should be explored before final conclusions are reached and additional studies of the performance of the WTC 7 building and related building performance issues should be conducted. These include the following:

a. Additional data should be collected to confirm the extent of the damage to the south face of the building caused by falling debris.

b. Determination of the specific fuel loads, especially at the lower levels, is important to identify possible fuel supplied to sustain the fires for a substantial duration. Areas of interest include storage rooms, file rooms, spaces with high-density combustible materials, and locations of fuel lines. The control and operation of the emergency power system, including generators and storage tanks, needs to be thoroughly understood. Specifically, the ability of the diesel fuel pumps to continue to operate and send fuel to the upper floors after a fuel line is severed should be confirmed.

c. Modeling and analysis of the interaction between the fire and structure are important. Specifically, the anticipated temperatures and duration of the fires and the effects of the fires on the structure need to be examined with an emphasis on the behavior of transfer systems and their connections.

d. Suggested mechanisms for a progressive collapse should be studied and confirmed. How the collapse of an unknown number of gravity columns brought down the whole building should be explained.

e. The role of the axial capacity between the beam-column connection and the relatively strong structural diaphragms may have had in the progressive collapse should be explained.

f. The level of fire resistance and the ratio of capacity-to-demand required for structural members and connection deemed to be critical to the performance of the building should be studied. The collapse of some structural members and connections may be more detrimental to the overall performance of the building than other structural members. The adequacy of current design provisions for members whose failure could result in large-scale collapse should also be studied.

Recommendations for Future Study

The Building Performance Study Team has developed recommendations for specific issues, based on the study of the performance of the WTC towers and surrounding buildings in response to the impact and fire damage that occurred. These recommendations have a broader scope than the important issue of building concepts and design for mitigating damage from terrorist attacks, and also address the level at which resources should be expended for aircraft security, how the fire protection and structural engineering communities should increase their interaction in building design and construction, possible considerations for improved egress in damaged structures, the public understanding of typical building design capacities, issues related to the study process and future activities, and issues for communities to consider if they are developing emergency response plans that include engineering response.

National Response. Resources should be directed primarily to aviation and other security measures rather than to hardening buildings against airplane impact. The relationship and cooperation between public and private organizations should be evaluated to determine the most effective mechanisms and approaches in the response of the nation to such disasters.

Interaction of Structural Elements and Fire. The existing prescriptive fire resistance rating method (ASTM E119) does not provide sufficient information to determine how long a building component can be expected to perform in an actual fire. A method of assessing performance of structural members and connections as part of a structural system in building fires is needed for designers and emergency personnel.

The behavior of the structural system under fire conditions should be considered as an integral part of the structural design. Recommendations are to:

- Develop design tools, including an integrated model that predicts heating conditions produced by the fire, temperature rise of the structural component, and structural response.

- Provide interdisciplinary training in structures and fire protection for both structural engineers and fire protection engineers.

Performance criteria and test methods of fireproofing materials relative to their durability, adhesion, and cohesion when exposed to abrasion, shock, vibration, rapid temperature rise, and high temperature exposures need further study.

Interaction of Structural and Fire Professionals in Design. The structural, mechanical, architectural, fire protection, blast, explosion, earthquake, and wind engineering communities need to work together to develop guidance for vulnerability assessment, retrofit, and design of concrete and steel structures to mitigate or reduce the probability of progressive collapse under single- and multiple-hazard scenarios.

An improved level of interaction between structural and fire protection engineers is encouraged. Specific recommendations are to:

- Consider behavior of the structural system under fire as an integral part of the design process.
- Provide cross-training of fire protection and structural engineers in the performance of structures and building fires.

Fire Protection and Engineering Discipline. The continued development of a system for performance-based design is encouraged. This involves the following:

- Improve the existing models that simulate fire and spread in structures, as well as the impact of fire and smoke on structures and people.
- Improve the database on material burning behavior.

Building Evacuation. The following topics were not explicitly examined during this study, but are recognized as important aspects of designing buildings for impact and fire events. Recommendations for further study are to:

- Perform an analysis of occupant behavior during evacuation of the buildings at WTC to improve the design of fire alarm and egress systems in high-rise buildings.
- Perform an analysis of the design basis of evacuation systems in high-rise buildings to assess the adequacy of the current design practice, which relies on phased evacuation.
- Evaluate the use of elevators as part of the means of egress for mobility impaired people as well as the general building population for the evacuation of high-rise buildings. In addition, the use of elevators for access by emergency personnel needs to be evaluated.

Emergency Personnel. One of the most serious dangers firefighters and other emergency responders face is partial or total collapse of buildings. Recommended steps to provide better protection to emergency personnel are:

- Have fire protection and structural engineers assist emergency personnel in developing broader pre-plans for buildings and structures to include more detailed assessments of hazards and response of structural elements and performance of buildings during fires, including identification of critical structural elements.
- Develop training materials and courses for emergency personnel with regards to effects of fire on steel.
- Review collaboration efforts between the emergency personnel and engineering professions so that engineers may assist emergency personnel in assessments during the time of the incident.

Education of Stakeholders. Stakeholders (e.g., owners, operators, tenants, authorities, designers) should be further educated about building codes, the minimum design loads typically addressed for building design, and the extreme events that are not addressed by building codes. Should stakeholders desire to address events not addressed by the building codes, they should have a basic understanding of developing and implementing strategies to mitigate damage from extreme events.

Stakeholders should also be educated about the expected performance of their building when renovations, or changes in use or occupancy, occur and the building is subjected to different floor or fire loads. For instance, if the occupancy in a building changes to one with a higher fire hazard, they should review the fire protection systems to ensure there is adequate fire protection. Or, if the structural load is increased with a new occupancy, the structural support system should be reviewed to ensure it can carry the new load.

Study Process. The report benefited from a tremendous amount of professional volunteerism due to the unprecedented level of national disaster. Improvements can be made that would aid the process for any future efforts. Recommendations are to:

- Provide resources that are proportional to the required level of effort.
- Provide better access to data, including building information, interviews, samples, site photos, and documentation.

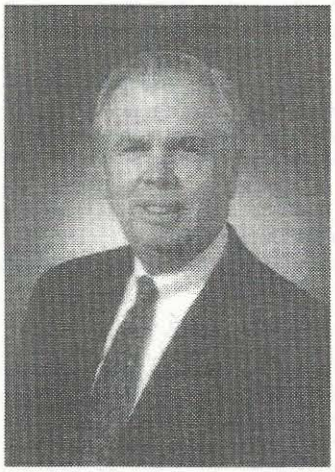
Archival Information. Archival information has been collected and provides the groundwork for continued study. It is recommended that a coordinated effort for the preservation of this and other relevant information be undertaken by a responsible organization or agency, capable of maintaining and managing such information. This effort would include:

- cataloging all photographic data collected to date;
- enhancing video data collected for both quality and timeline;
- conducting interviews with building occupants, witnesses, rescue workers and any others that may provide valuable information; and
- initiating public requests for information.

Conclusion

ASCE is proud of the work done by the BPS Team, but strongly believes that the follow up studies recommended by the FEMA/ASCE Report are critical to obtaining the technical knowledge needed by engineers for future building design.

Thank you for the opportunity to express ASCE's views. We offer you and all of the agencies involved in the recovery efforts ASCE's full resources to manage the nation's critical infrastructure needs. We are ready to help in any way possible, and are eager to hear from you regarding ways that ASCE's Critical Infrastructure Response Initiative can support you as you examine our infrastructure needs in the coming months.



○ **W. Gene Corley**
Senior Vice President
gcorley @ c-t-l.com

Educational Background •
University of Illinois
B.S. Civil Engineering, 1958
M.S. Structural Engineering, 1960
Ph.D. Structural Engineering, 1961

Registration •
Licensed Structural Engineer - Illinois
Licensed Professional Engineer - Illinois
Registered Civil Engineer - California, Hawaii
Registered Professional Engineer - Alabama, Florida, Kansas, Louisiana, Michigan, Mississippi, Missouri, Pennsylvania, South Dakota, Tennessee, Texas, Utah, Virginia, Washington
Chartered Engineer, FI Struct E, UK

CTL Experience • Dr. Corley has served as CTL Vice President since 1987. In this position, he serves as CTL's managing agent for professional and structural engineering and leads structural evaluation projects related to industrial, transportation and parking facilities, bridges and buildings. He also is active in projects related to earthquake engineering. His wide range of experience includes evaluation of earthquake and blast damaged buildings and bridges; investigation of distress in prestressed concrete structures; repair of parking garages damaged by corrosion; evaluation and repair of high rise buildings, stadiums, silos and bridges; design and construction of repairs for prestressed and conventionally-reinforced, precast and cast-in-place concrete and structural steel facilities. In 1995, Dr. Corley was selected by ASCE to lead a Building Performance Assessment Team investigating the bombing of the Murrah Federal Building in Oklahoma City.

Prior Experience • After receiving his B.S. degree, Dr. Corley worked for the Shelby County, Illinois highway department where he designed highways and bridges. He then returned to the University of Illinois as a research assistant and National Science Foundation teaching fellow while pursuing his graduate studies.

Upon completion of his Ph.D., he served as a commissioned officer in the U.S. Army from 1961 until 1964. During this period, Dr. Corley was a research and development coordinator with the U.S. Army Corps of Engineers at Fort Belvoir, Virginia. His duties included bridge design, acceptance testing of mobile floating assault bridge equipment, design of tank launched bridges and fatigue testing of bridges fabricated from high strength steel, aircraft aluminum and titanium alloys.

In 1964, Dr. Corley began work as a development engineer with the Portland Cement Association. While serving in successively more responsible positions, he was directly involved in the development of improved design procedures for structural concrete, concrete pavement, railroads and structures subjected to fire loads. In addition, he served on an earthquake damage investigation team, carried out investigations of damaged or deteriorated structures and developed repair procedures for numerous buildings and bridges.

Publications and Professional Activities•
W. Gene Corley has authored more than 150 technical papers and books. He frequently lectures to technical and non-technical groups on the subjects of prevention of failures, effects of earthquakes and design and repair of structures. He regularly presents training courses on reinforced concrete design and teaches the seismic design portion of a refresher course to candidates for the Illinois Structural Engineering License examination.

Dr. Corley chaired ACI Committee 318 for six years as the committee developed the 1995 Building Code Requirements for Structural Concrete. He also serves on several other national and international committees that prepare recommendations for structural design and for design of earthquake resistant buildings and bridges. His professional activities resulted in his receiving 11 national awards including the Best Structural Publication Award from NCSEA, Outstanding Paper from the ASCE Journal of Performance of Constructed Facilities, the Wason Award for research from ACI, the T.Y. Lin Award from ASCE and the Martin Korn Award for PCI. He also has received several regional awards, including the UIUC Civil Engineering Alumni Association's Distinguished Alumnus Award, the SEAOI Service Award, Illinois ASCE Structural Division's Lifetime Achievement Award, the Henry Crown Award, and the SEAOI John Parmer Award.

Dr. Corley serves or has served in leadership roles for numerous professional organizations, both national and international, including the following:

American Society of Civil Engineers (Fellow)
National Society of Professional Engineers (Member)
National Council of Structural Engineers Associations (Founding Member, Board of Direction, Former President)
American Concrete Institute (Fellow) Former Chairman, Committee on Standard Building Code
American Railway Engineering Association (Member)
Building Seismic Safety Council (Former Vice-Chairman and Founding Member, Board of Direction)
Chicago Committee on High Rise Buildings (Member and Former Chairman)
Earthquake Engineering Research Institute (Member and Former President, Great Lakes Chapter)
Institution of Structural Engineers, UK (Fellow)
International Association for Bridge and Structural Engineering (Member)
National Academy of Engineering (Member)
National Association of Railroad Safety Consultants and Investigators (Member)
NACE International (Member)
Prestressed Concrete Institute (Member)
RILEM (Member)
Post Tensioning Institute (Member)
Transportation Research Board (Member)
Structural Engineers Association of Illinois (Member, Former President)
Governor's Earthquake Preparedness Task Force (Illinois)

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March 18, 2002

The Honorable Sherwood Boehlert
Chairman
Committee on Science
U.S. House of Representatives
2320 Rayburn Building
Washington, D.C. 20515-6307

Dear Mr. Chairman:

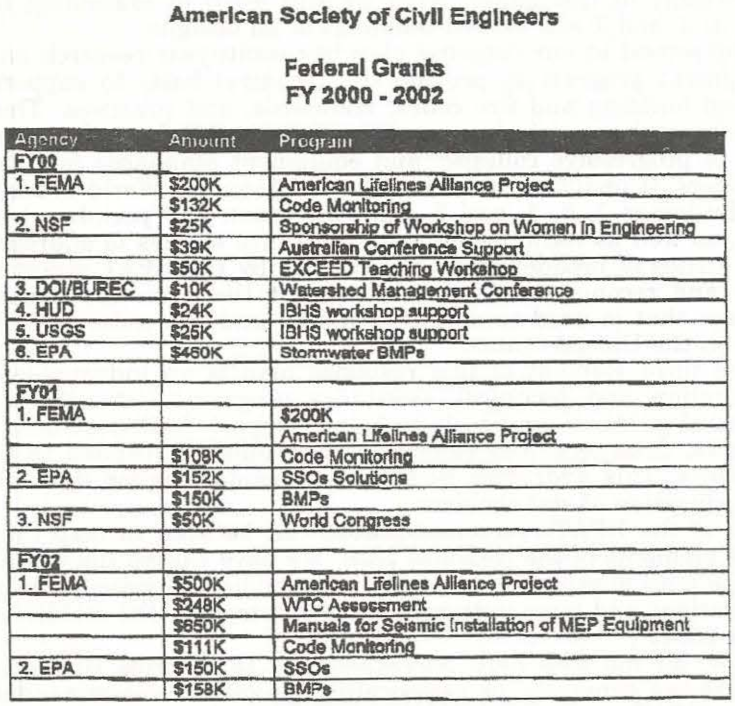
On behalf of the American Society of Civil Engineers, a witness before the Subcommittee, we declare, pursuant to House Rule IX, clause 2(g)(4), that Gene Corley, Senior Vice President at CTL Engineering in Chicago, IL, and CTL have received the following federal grants in the past three years: U.S. Department of Transportation $975; Department of the Navy $9,900; and U.S. Department of Justice $95,136.

Additionally, the American Society of Civil Engineers has received the following grants in the last three years, please see attached sheet.

Sincerely yours,

Brian Pallasch
Director, Government Relations

Civil Engineers - Designers and Builders of the Quality of Life



American Society of Civil Engineers

Federal Grants
FY 2000 - 2002

Agency	Amount	Program
FY00		
1. FEMA	$200K	American Lifelines Alliance Project
	$132K	Code Monitoring
2. NSF	$25K	Sponsorship of Workshop on Women in Engineering
	$39K	Australian Conference Support
	$50K	EXCEED Teaching Workshop
3. DOI/BUREC	$10K	Watershed Management Conference
4. HUD	$24K	IBHS workshop support
5. USGS	$25K	IBHS workshop support
6. EPA	$460K	Stormwater BMPs
FY01		
1. FEMA		$200K
		American Lifelines Alliance Project
	$108K	Code Monitoring
2. EPA	$152K	SSOs Solutions
	$150K	BMPs
3. NSF	$50K	World Congress
FY02		
1. FEMA	$500K	American Lifelines Alliance Project
	$248K	WTC Assessment
	$650K	Manuals for Seismic Installation of MEP Equipment
	$111K	Code Monitoring
2. EPA	$150K	SSOs
	$158K	BMPs

Chairman BOEHLERT. Thank you very much, Dr. Corley. Dr. Bement.

STATEMENT OF DR. ARDEN L. BEMENT, JR., DIRECTOR, NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, U.S. DEPARTMENT OF COMMERCE

Dr. BEMENT. Thank you, Mr. Chairman, Mr. Hall, and, members of the Committee. I want to thank you for this opportunity to testify on the NIST proposed investigation into the collapse of the World Trade Center buildings.

I will outline the proposed NIST response plan and show how it complements and is responsive to the efforts of the FEMA/ASCE Building Performance Assessment Team. I commend Dr. Corley and the BPAT members for their report and detailed recommendations.

The NIST proposed response plan consists of three key program elements, including an investigation to be conducted in parallel with, first, a 24-month building and fire safety investigation into the collapse of the Twin Towers and World Trade Center Building 7. The goal here is to investigate the building construction, the materials used, and the technical conditions that combined to cause these disasters following the initial impact of the aircraft. While

World Trade Center Buildings 4, 5, and 6 will not be investigated specifically in this phase, what we will learn in examining Buildings 1, 2, and 7 will benefit buildings of all designs.

The second in our response plan is a multi-year research and development program to provide the technical basis to support improved building and fire codes, standards, and practices. This addresses work in critical areas such as structural fire safety, prevention of progressive collapse, and equipment standards for first responders. It includes BPAT recommendations for World Trade Center Buildings 3, 4, 5, and 6, Bankers Trust, and peripheral buildings, as well as recommendations for future studies to address specific issues of broader scope not covered by the BPAT report. Outputs and recommendations will support the voluntary consensus process that is used to develop building and fire codes and standards in the United States.

The third element of this response plan is an industry-led dissemination and technical assistance program that will provide practical guidance and tools to better prepare facility owners, contractors, designers, and emergency personnel to respond to future disasters. This addresses BPAT recommendations for the training and education of stakeholders.

All of the BPAT recommendations can be seen to map into the three elements of the response plan. We have shared the overall response plan approach extensively with public and private sector organizations and have welcomed their inputs since the middle of October 2001.

Now, let me stop here parenthetically to describe this graphic. This shows generally, or generically, the various recommendations in the BPAT report, and the items that are shown in white will be included in the investigation. The items in yellow will be the focus of the research and development phase of the program, and the items shown in blue will be addressed during the dissemination and technical assistance phase of the response program.[1]

Our overall plan was modified in January 2002 when FEMA requested NIST to initiate an investigation under NIST's unique legislative authorities to conduct structural and fire investigations. This request was in direct response to a growing demand for a broad-based, Federal investigation into the World Trade Center disaster from technical experts, industry leaders, and families of building occupants and first responders who lost their lives on September 11, 2001.

We continue to revise the plan as more technical information becomes available, and to be responsive to the suggestions and needs of these many stakeholders. We agree with the BPAT recommendations that additional study of the Twin Towers and World Trade Center Building 7 should be conducted. The NIST investigation will focus on these buildings. We believe strongly that the results of such an investigation could lead to major changes in both U.S. building and fire codes and in engineering practice. We also believe strongly that the lessons to be derived from such an investigation will be applicable to a broad range of building types, not just the specific buildings that are studied.

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[1] Please refer to Slide 2 of Dr. Bement's written statement; *see p. 82.*

Let me now give you some specific examples to illustrate why we believe this to be the case. These building disasters provide a unique source of information to study the safety and performance of open-web steel trussed joists under fires. This type of trussed joist is used widely in floor and roof systems for commercial and institutional buildings nationwide.

New mechanisms, not considered previously, can be studied that could initiate progressive collapse in buildings as a result of fires and impact loads, including the critical role of pivotal components such as transfer girders and floor diaphragms.

In addition, the mechanical and metallurgical behavior of many different grades of structural steel under fires, using steel recovered from the World Trade Center site, that is now being stored at NIST, can also be investigated.

There are equally important lessons for life safety. First of all, are fire fighting technologies and practices for tall buildings, including occupant behavior, evacuation, emergency response, and the performance of built-in fire protection systems, such as sprinklers and fire alarms. Also, is the control of fire spread in buildings with large, open floor spaces, and the effectiveness in compartmentalization as a means to isolate fires in such buildings.

There are also important lessons to be learned for engineering practice, such as the performance of the design, construction, and approval process used to ensure safety whenever an innovation structural system is used or where there is a need for variances from building and fire codes.

The provision of adequate structural reserve capacity to accommodate abnormal loads, such as blasts, impact, and accidental fires, especially those that can be anticipated prior to construction, balanced properly against the need to achieve design efficiency is also important.

The proposed NIST investigation will include world-class technical expertise from both within and outside of NIST. External experts will be drawn from both academia and practice, and several of those may well have contributed to the BPAT study. We propose to charter a Federal Advisory Committee to guide all aspects of the NIST investigation, including the review of major investigation reports.

We will maintain ongoing liaison with the professional communities over the course of the investigation through periodic briefings, presentations, and opportunities for comment on key investigation reports.

NIST will assign a special liaison to interact with the families of building occupants and first responders. We recognize the vital role that these individuals and groups have to play in providing input on the scope of the proposed NIST investigation. We also understand that it is appropriate and important to keep these families and organizations informed about the progress of the proposed investigation.

A summary of the proposed NIST investigation plan is attached for the record and is being made available to the general public on the NIST website beginning today. NIST will use an open and inclusive process in planning and conducting the investigation and in publishing its findings and recommendations.[2]

We have and are consulting extensively with technical experts and groups in developing our plan. We have consulted with local authorities in New York who have expressed support for NIST and agreed to cooperate in its investigation. We will hold a public meeting in New York City in the near future to share the details of the proposed NIST plan which will be made available in detail for the general public two weeks prior to the meeting, and will seek the public's informed comment on its scope and each of the elements as we make the plan final.

The Administration has expressed strong commitment for the NIST response plan and has requested $16 million as part of the FEMA's fiscal year 2002 supplemental budget request to support the NIST investigation. The President's fiscal year 2003 budget request also includes $2 million in base funding to support other elements of the NIST response plan. And we have already redirected approximately $2 million of existing base funds within our Building and Fire Research Laboratory to support the response plan. Future resource requirements for the broader research and development and dissemination and technical assistance program will be included in our fiscal year 2004 budget process and beyond.

Finally, Mr. Chairman, I look forward to working with you and members of this Committee as NIST embarks on a very important technical investigation. FEMA and NIST are committed to ensuring a smooth transition. Mr. Robert Shea and I recently signed a Memorandum of Understanding to strengthen our collaborative bonds by designating NIST to serve as a research and technical resource for FEMA. With your permission, I would like to submit a copy of that Memorandum of Understanding for the record.[3]

Chairman BOEHLERT. Without objection, so ordered.

Dr. BEMENT. We have agreed to develop and sign, by the end of May, an operational protocol for a quick deployment mechanism that could be activated when a NIST response to extreme events is needed.

This concludes my prepared written remarks, and I will be glad to answer any questions from the Committee.

[The prepared statement of Dr. Bement follows:]

PREPARED STATEMENT OF ARDEN L. BEMENT, JR.

Chairman Boehlert, Ranking Member Hall, and Members of the Committee, I want to thank you for this opportunity to testify on the National Institute of Standards and Technology's proposed investigation into the collapse of the World Trade Center (WTC) buildings.

I will outline the proposed *NIST response plan* today, and show how it complements and is responsive to the efforts of the Building Performance Assessment Team, or BPAT, led by the American Society of Civil Engineers (ASCE) and sponsored by the Federal Emergency Management Agency, FEMA. The response plan addresses all major recommendations contained in the BPAT report. I commend Dr. Gene Corley and the BPAT members for their excellent report and detailed recommendations. The National Institute of Standards and Technology (NIST) has also identified other critical issues that need study, especially in areas that impact life safety and engineering practice.

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[2] The summary follows the written statement of Dr. Bement; *see p. 54.*

[3] The MOU follows the written statement of Dr. Bement; *see p. 84.*

The NIST proposed response plan consists of three key program elements—including an investigation—to be conducted in parallel *(graphic to be projected on video monitors)*. These are:

- First, a 24-month *building and fire safety investigation* into the collapse of the Twin Towers (WTC 1 and 2) and WTC 7. The goal of this program element is to investigate the building construction, the materials used, and the technical conditions that combined to cause these disasters following the initial impact of the aircraft. While WTC 4, 5,and 6 will not be investigated specifically in this phase, what we learn in examining WTC 1, 2 and 7 would benefit buildings of all designs.
- Second, a multi-year *research and development (R&D) program* to provide the technical basis to support improved building and fire codes, standards, and practices. This program element addresses work in critical areas such as structural fire safety, prevention of progressive collapse, and equipment standards for first responders. It includes BPAT recommendations for WTC 3, 4, 5, and 6, Bankers Trust, and peripheral buildings as well as recommendations for future studies to address specific issues of broader scope not covered by the BPAT. The program outputs and recommendations will support the voluntary consensus process that is used to develop building and fire codes and standards in the United States.
- Third, an industry-led *dissemination and technical assistance program (DTAP)* that will provide practical guidance and tools to better prepare facility owners, contractors, designers, and emergency personnel to respond to future disasters. The DTAP will also be an important complement to the R&D effort to demonstrate and gain acceptance of proposed changes to practice, standards, and codes. This program element addresses BPAT recommendations for the training and education of stakeholders.

All the BPAT recommendations can be seen to map into the three above elements in this graphic *(graphic on screen)*.

We have shared the overall response plan approach extensively with public and private sector organizations and have welcomed their inputs since the middle of October 2001. The plan was modified in January 2002 when FEMA requested NIST to initiate an investigation under NIST's unique legislative authorities to conduct structural and fire investigations. This request was in direct response to a growing demand for a broad-based federal investigation into the World Trade Center disaster from technical experts, industry leaders, and families of building occupants and first responders who lost their lives on September 11, 2001. We continue to revise the plan as more technical information becomes available and to be responsive to the suggestions and needs of these many stakeholders.

The Commerce Department and NIST have received letters supporting our proposed response plan from key industry leaders responsible for U.S. building and fire standards, codes, and practices, including the American Society of Civil Engineers, the National Fire Protection Association, the American Institute of Architects, the Council on Tall Buildings and Urban Habitat, the Construction Industry Institute, the Society of Fire Protection Engineers, and the International Association of Fire Chiefs.

We agree with the BPAT recommendations that additional study of the Twin Towers and WTC 7 should be conducted. The NIST investigation will focus on these buildings. We believe strongly that the results of such an investigation could lead to major changes in both U.S. building *and* fire codes and in engineering practice, despite the unique design features or circumstances under which the buildings collapsed. We also believe strongly that the lessons to be derived from such an investigation will be applicable to a broad range of buildings types, not just the specific buildings that are studied. Let me now give you some examples to illustrate why we believe this to be the case.

The Twin Towers and WTC 7 are the only known cases of total structural collapse where fires played a significant role. These disasters provide a unique source of information to understand the complexities associated with the dynamics of real building fires and the collapse vulnerability of buildings to fires. We expect to analyze that information to validate generally applicable methodologies for use in fire safety design and retrofit of structures, and to evaluate the performance of fireproofing materials and connections used in steel structures.

In addition, these building disasters provide a unique source of information to study:

- The safety and performance of open-web steel trussed joists under fires. This type of trussed joist is used widely in floor and roof systems for commercial and institutional buildings nationwide.
- New mechanisms—not considered previously—that could initiate progressive collapse in buildings as a result of fires and impact loads, including the critical role of pivotal components such as transfer girders and floor diaphragms.
- The mechanical and metallurgical behavior of many different grades of structural steel under fires using steel recovered from the WTC site that is being stored at NIST.

There are equally important lessons for life safety—which were outside the scope of the BPAT study:

- Firefighting technologies and practices for tall buildings, including occupant behavior, evacuation, emergency response, and the performance of built-in fire protection systems such as sprinklers and fire alarms.
- The control of fire spread in buildings with large open floor plans, and the effectiveness of compartmentation as a means to isolate fires in such buildings.

There are also important lessons to be learned for engineering practice—areas that were not the focus of the BPAT study:

- The performance of the design, construction, and approval processes used to assure safety whenever an innovative structural system is used or there is a need for variances from building and fire codes.
- The provision of adequate structural reserve capacity to accommodate abnormal loads such as blast, impact, and accidental fires—especially those that can be anticipated prior to construction—balanced properly against the need to achieve design efficiency.

The proposed NIST investigation will include world-class technical expertise from both within and outside NIST. External experts will be drawn from both academia and practice and several of those may well have contributed to the BPAT study.

We propose to charter a Federal Advisory Committee to guide all aspects of the NIST investigation, including the review of major investigation reports. Members of this group will be recognized for their distinguished professional service, possess broad technical expertise and experience, and have a reputation for independence, objectivity, and impartiality.

I have appointed a Secretariat within NIST to coordinate NIST-level activities in support of the WTC investigation and to maintain ongoing liaison with members of Congress, the public, and the media.

NIST will assign a special liaison to interact with the families of building occupants and first responders. We recognize the vital role that those individuals and groups have to play in providing input on the scope of the proposed NIST investigation. We also understand that it is appropriate and important to keep these families and organizations informed about the progress of the proposed investigation.

We will maintain ongoing liaison with the professional communities over the course of the investigation through periodic briefings, presentations, and opportunity for comment on key investigation reports.

A summary of the proposed NIST investigation plan is attached for the record and is being made available to the general public on the NIST website beginning today. NIST will use an open and inclusive process in planning and conducting the investigation, and in publishing its findings and recommendations. We consulted extensively with technical experts and groups in developing the plan and briefed the BPAT experts at their January 2002 meeting, and again last Wednesday. Yesterday, we briefed representatives of the parent organizations comprising the BPAT coalition. We will hold a public meeting in New York City in the near future to share the details of the proposed NIST plan, which will be made available to the general public two weeks prior, and seek the public's informed comment on its scope before we adopt the plan as final.

Following our statutory requirements, before we begin a building investigation, we consult with local authorities. In this case, we consulted with local authorities in New York, including the Port Authority of New York and New Jersey, the Mayor's Office of Emergency Management, the New York City Department of Design and Construction, and the Fire Department of New York. These organizations have expressed written support for NIST and agreed to cooperate in its investigation.

The Administration has expressed strong commitment for the NIST response plan and has requested $16 million as part of the Federal Emergency Management Agency's FY 2002 supplemental budget request—now in Congress—to support the NIST investigation. The President's FY 2003 budget request to Congress also requests an increase of $2 million in base funding to support other elements of the NIST response plan. The Building and Fire Research Laboratory within NIST has already redirected approximately $2 million of its existing base funds to support the response plan. Future resource requirements for the broader research and development and dissemination and technical assistance program will be considered in the Fiscal Year 2004 budget process and beyond.

Finally, Mr. Chairman, I look forward to working with you and members of this Committee as NIST embarks on a very important technical investigation. FEMA and NIST are committed to ensuring a smooth transition. Mr. Robert Shea and I recently signed a Memorandum of Understanding to strengthen our collaborative bonds by designating NIST to serve as a research and technical resource for FEMA. With your permission, I would like to submit a copy of that MOU for the record. We have agreed to develop and sign, by the end of May 2002, an operational protocol for a quick deployment mechanism that could be activated when a NIST response to extreme events is needed.

This concludes my prepared remarks. I will be pleased to answer your questions.

[The attachments to Dr. Bement's statement follow:]

Proposed Plan
National Institute of Standards and Technology
National Building and Fire Safety Investigation of the World Trade Center Disaster

Goals:

- To investigate the building construction, the materials used, and the technical conditions that contributed to the outcome of the World Trade Center (WTC) disaster.
- To serve as the basis for:
  - Improvements in the way buildings are designed, constructed, maintained, and used;
  - Improved tools, guidance for industry and safety officials;
  - Revisions to codes, standards, and practices; and
  - Improved public safety.

Objectives:

The primary objectives of the NIST-led technical investigation of the WTC disaster are to:

1. Determine why and how the World Trade Center Buildings collapsed after the initial impact of the aircraft;
2. Determine why the injuries and fatalities were so low or high depending on location, including all technical aspects of fire protection, response, evacuation, and occupant behavior and emergency response;
3. Determine the procedures and practices that were used in the design, construction, operation, and maintenance of the World Trade Center Buildings; and
4. Identify, as specifically as possible, building and fire codes, standards, and practices that warrant revision and are still in use.

Guiding Principles:

- Aggressive, comprehensive, thorough, independent, and objective technical investigation that is fully informed of the concerns and issues of all interested parties and within the limits of available resources.
- Open and inclusive process in planning and conducting the investigation, and in publishing and disseminating findings and recommendations.
- Focus on fact-finding and analysis of the facts, validating/verifying existing knowledge, and creating new technical and/or scientific knowledge for the purpose of improving practice, standards, and codes and to reduce future risks.
- Non-technical issues are outside scope of investigation: No findings of fault or negligence of any individual or organization.

Source of Information for Plan Development:

Formulation of the NIST investigation plan will draw on many sources of information and embrace information from outside NIST. These include external experts and groups (industry, academia, and government), FEMA/ASCE Building Performance Assessment Team (BPAT) study (FEMA Report 403, May 2002), NIST experts in building and fire safety, and the public-at-large. NIST will hold a public meeting in New York City on June 24, 2002 to gather comments and suggestions on the scope of the NIST investigation detailed in this plan. Written public comments also will be accepted (e-mail: wtc@nist.gov, fax: 301-975-6122), preferably before June 30, 2002. The refined plan will be made available for public comment before it is adopted as final.

Program Context for the Investigation:
The ***NIST response plan*** consists of three key program elements – including an investigation – to be conducted in parallel (see attached graphic #1). These are:

- First, a 24-month ***building and fire safety investigation*** into the factors contributing to the probable cause of collapse of the Twin Towers (WTC 1 and 2) and WTC 7. The goal of this program element is to investigate the building construction, the materials used, and the technical conditions that contributed to the outcome of these disasters following the initial impact of the aircraft. What is learned in examining WTC 1, 2 and 7 is expected to benefit buildings of all designs.

- Second, a multi-year ***research and development (R&D) program*** to provide the technical basis for improved building and fire codes, standards, and practices. This program element addresses work in critical areas such as structural fire safety, prevention of progressive collapse, and equipment standards for first responders. It includes BPAT recommendations for WTC 3, 4, 5, and 6, Bankers Trust, and peripheral buildings as well as recommendations for future studies to address specific issues of broader scope not covered by the BPAT. Outputs and recommendations will be introduced into the voluntary consensus process that is used to develop building and fire codes and standards in the U.S.

- Third, an industry-led ***dissemination and technical assistance program (DTAP)*** that will provide practical guidance and tools to better prepare facility owners, contractors, designers, and emergency personnel to respond to future disasters. The DTAP will also be an important complement to the R&D effort in gaining acceptance of proposed changes to practice, standards, and codes. In addition, it will address BPAT recommendations for training and education of stakeholders.

The NIST response plan complements, is responsive to – and goes beyond – the BPAT efforts. The plan addresses all major recommendations contained in the BPAT report (see attached graphic #2). NIST has also identified other critical issues that need study, especially in areas that impact life safety and engineering practice.

Scope and Rationale for Investigation:
NIST agrees with the BPAT recommendations that additional studies of the Twin Towers and WTC 7 should be conducted. The NIST investigation – one component of the proposed NIST response plan – will focus on these buildings. The results of such an investigation could lead to major changes in both U.S. building and fire codes and in engineering practice, despite the unique design features or circumstances under which the buildings collapsed. The lessons to be derived from such an investigation will be applicable to a broad range of buildings types, not just the specific buildings that are studied. The following examples are illustrative:

The Twin Towers and WTC 7 are the only known cases of total structural collapse where fires played a significant role. These disasters provide a unique source of information to understand the complexities associated with the dynamics of building fires and the collapse vulnerability of buildings to fires. The investigation expects to analyze that information to validate generally applicable methodologies for use in fire safety design and retrofit of structures, and to evaluate the performance of fireproofing materials and connections used in steel structures.

In addition, these building disasters provide a unique source of information to investigate:

- The safety and performance of open-web steel trussed joists under fires. This type of trussed joist is used in commercial and institutional buildings nationwide.
- New mechanisms – not considered previously – that could initiate progressive collapse in buildings as a result of fires and impact loads, and the critical role of pivotal components such as transfer girders and floor diaphragms.
- The mechanical and metallurgical behavior of many different grades of structural steel under fire using steel recovered from the WTC site that is being stored at NIST.

There are equally important lessons for life safety – which were outside the scope of the BPAT study.

- Firefighting technologies and practices for tall buildings, including occupant behavior, evacuation, emergency response, and the performance of active fire protection systems such as sprinklers, manual suppression, fire alarms, and smoke management systems.
- The control of fire spread in buildings with potentially large open floor plans, and the effectiveness of compartmentation as a means to isolate fires in such buildings.

There are also important lessons for engineering practice that were not the focus of the BPAT study.

- The performance of the design, construction, and approval processes used to assure safety whenever an innovative structural system is used or there is a need for variances from building and fire codes – and whether such practices are adequate to detect and remedy inherent vulnerabilities.
- The provision of adequate structural reserve capacity to accommodate abnormal loads such as blast, impact, and accidental fires – especially those that can be anticipated prior to construction – balanced properly against the need to achieve design efficiency.

The NIST investigation will strive to study the disaster holistically, paying particular attention to the interplay between the building, the occupants, and the emergency responders. The review, analysis, modeling, and re-creation testing work will be based upon a solid foundation of technical evidence provided by building documents, video and photographic records, oral history data, emergency response records, and recovered structural steel.

Technical Approach:
The technical approach of the NIST investigation will include the following phases over an estimated 24 month period:

- **Identification of Technical Issues and Major Hypotheses Requiring Investigation:** opportunity for public input (e.g., open meeting; website; Federal Register notice) in developing investigation plan; expert panels to solicit input (experts in structural and fire protection engineering; experts in construction, maintenance, operation and emergency response procedures of tall buildings); findings and recommendations of FEMA-funded BPAT study and technical issues identified by other experts; analysis of inputs to establish priorities for investigation; review by Federal Advisory Committee.
- **Data Collection**: inputs from building owners and operators, local authorities, consultants, and contractors; data and information collected by the FEMA/ASCE BPAT study; building and fire protection design calculations, records, plans, and specifications; construction, maintenance, operation records, building renovations and upgrades; video and photographic data; field data; interviews and other oral and written accounts from building occupants,

families of victims, emergency responders, building operators, and other witnesses; emergency response records including audio communications; and other records.

- **Analysis and Comparison of Building and Fire Codes and Practices:** analysis and comparisons of codes and standards then and now, and specifications used for WTC buildings; review and analysis of practices used for design, construction, operation, maintenance, repair, renovations, and upgrades.

- **Collection and Analysis of Forensic Evidence:** structural steel, material specimens and other forensic evidence to the extent they have been collected or are otherwise available; metallurgical and mechanical analysis of steel to evaluate quality and estimate maximum temperatures; analysis of fire and elevator control panels.

- **Modeling, Simulation, and Scenario Analysis:** aircraft impact on structures and estimated damage to interior and core structure and residual structural capacities; role of jet fuel and building contents in resulting fire; fire dynamics and smoke movement; thermal effect on structures and the effectiveness of fireproofing; effect of fire on structural response and vulnerability and the role of connections, flooring system, and core and exterior columns; occupant behavior and response including influence of communications and barriers to egress; evacuation issues including egress, control/fire panels, emergency response, and communications; fire protection system design and vulnerability; hypotheses for structural collapse including evaluation of system vulnerability to progressive collapse; probable collapse mechanisms and associated uncertainties.

- **Testing to Re-Create Scenarios and Failure Mechanisms:** small and some real-scale re-creation tests to provide additional data and verify simulation predictions, especially for the effects of fires (e.g., use and adequacy of standard fire ratings, behavior of connections and assemblies).

- **Technical Findings and Recommendations:** preparation of interim and final reports; peer review by established NIST Editorial Review Board; augmented NIST review to include senior management and legal; review by Federal Advisory Committee; public comment period; finalize and disseminate via published reports, web, and media.

- **Dissemination and Deployment of Findings:** develop and disseminate proposed changes to codes and standards based on findings; participate with industry and emergency response community in their adoption and acceptance into codes and standards.

Currently, the NIST investigation plan includes eight projects that would provide the focus for the technical work. These are: (1) analysis of building and fire codes and practices; (2) baseline structural performance and aircraft impact damage prediction; (3) forensic analysis of structural steel; (4) investigation of active fire protection systems; (5) prediction of the thermal and tenability environment; (6) structural fire response and collapse; (7) occupant behavior, egress, and emergency communications; and (8) fire service technologies and guidelines. These projects are interdependent, and when considered together will meet the NIST investigation objectives (see attached graphic #3). The graphic shows how each project contributes to the investigation objectives – some projects contribute to more than one objective. A detailed description of each of these eight projects is in Attachment 1.

Technical Expertise:
The NIST investigation will use world-class technical expertise from both within and outside NIST. External experts will be drawn from academia, practice, and government and used on an as needed basis in various phases of the investigation. Several of these experts may well have contributed to the BPAT study.

Federal Advisory Committee:
NIST will charter a Federal Advisory Committee to help guide all aspects of the NIST investigation. The Committee will provide advice on scope, approach, work plan, and schedule; review and provide advice on results, findings, and recommendations; and review and provide advice on interim and final technical reports. Committee meetings will be announced in the Federal Register. Members of the Panel will be recognized for distinguished professional service, possess broad technical expertise and experience, and have a reputation for independence, objectivity, and impartiality. Members shall reflect the wide diversity of technical disciplines and competencies involved in the WTC investigation, including structural engineering, fire protection engineering, metallurgy, firefighting, human behavior, and property insurance. Members of this committee will be selected to avoid conflicts of interest – they shall not: be current or former NIST employees, be the recipient of an active NIST grant or contract, represent or be affiliated with parties affected directly by the investigation, participate in the conduct of the investigation, or participate in litigation on matters directly and specifically within the scope of the NIST investigation. The Advisory Committee will provide independent review of the NIST investigation ensuring that it is conducted objectively, thoroughly, and with the highest integrity.

NIST Secretariat:
The Director of NIST has established a secretariat to coordinate NIST-level activities in support of the investigation and to maintain ongoing liaison with the Executive Branch, the Congress, the public, and the media. NIST recognizes that there will be significant public and media interest in the investigation. NIST has assigned a spokesperson to provide press announcements and coordinate media briefings during the course of the investigation. NIST will also provide information via reports and briefings to the Executive Branch and the Congress at their request. The secretariat includes representatives of the Building and Fire Research Laboratory, Congressional and Legislative Affairs, Budget, Public and Business Affairs, NIST Counsel, Program Office, Acquisition and Logistics, Occupational Health and Safety, and the Management and Organization Division.

Liaison with the Professional Community, the Public, and Local Authorities:
NIST will maintain ongoing liaison with the professional community, the public, and local authorities over the course of the investigation through briefings, presentations, and opportunity for comment on key investigation reports. NIST will assign a special liaison to interact with the families of building occupants and first responders. NIST recognizes the vital role that those individuals and groups have to play in providing input on the NIST investigation. NIST also believes that it is appropriate and important to keep these families and organizations informed about the progress of the investigation.

Impact and Outcomes:
The NIST investigation will be valuable in establishing the probable technical causes of the disaster after aircraft impact, replacing speculative observations with objective and fact-based findings, deriving lessons learned from the disaster, and identifying needed improvements to building and fire standards, codes, and practices and to the safety of tall buildings nationwide. Implementation of the results of the NIST investigation – in conjunction with those of the R&D

and Dissemination and Technical Assistance elements of the NIST response plan – will help restore public confidence by making tall buildings safer nationwide, enhance the effectiveness and safety of fire and emergency responders, and better protect building occupants and property in the future.

The results of the NIST investigation will also support and guide future work to develop and disseminate guidance and tools, assess and reduce vulnerabilities, and produce the technical basis for cost-effective changes in national practices and standards. A private sector coalition – representing the key industry, standards, codes, and professional organizations – has worked with NIST to establish the response plan (see page 1) to meet these longer-term needs. The goal of the longer-term program is to produce cost-effective retrofit and design measures, and operational guidance for building owners and emergency responders.

Performance Outputs for WTC Investigation

National Building and Fire Safety Investigation of the World Trade Center Disaster		
Technical Area	**Project #**	**Outputs**
Identification of Technical Issues and Major Hypotheses	**Planning Phase**	• Public Meeting to gather comments on scope of NIST investigation plan. • Report(s) on NIST Investigation Plan Approach and Process. • Major Hypotheses and Technical Issues for Investigation
Analysis of Building and Fire Codes and Practices	1	• Report(s) on Analysis of Building and Fire Codes and Practices to determine the procedures and practices that were used in the design, construction, and maintenance of the structural, passive fire protection, and emergency access and evacuation systems of the World Trade Center Buildings 1, 2, and 7, and to provide input to other investigation projects.
Baseline Structural Performance and Aircraft Impact Damage Prediction	2	• Report(s) on Baseline Structural Performance and Aircraft Damage Prediction to evaluate the role of structural system design and the abnormal loads from aircraft impact on the collapse of the WTC towers.
Forensic Analysis of Structural Steel	3	• Report(s) on Forensic Analysis of Structural Steel to determine properties and quality of the metal, weldments, and connections, and to provide data for other investigation projects.
Investigation of Active Fire-Protection Systems	4	• Report(s) on Investigation of Active Fire-Protection Systems to document and evaluate their performance on September 11, 2001 and to assess their role in fire spread, emergency response, and the fate of occupants and responders.
Prediction of Thermal Environment	5	• Report(s) on Prediction of Thermal and Tenability Environment for use in evaluating the behavior and fate of occupants and responders and the structural performance of the buildings.
Structural Fire Response and Collapse	6	• Report(s) on Structural Fire Response and Collapse to identify most probable structural collapse mechanisms for World Trade Center Buildings 1, 2, and 7.
Occupant Behavior, Egress, and Emergency Communications	7	• Report(s) on Occupant Behavior, Egress, and Emergency Communications to determine the behavior and fate of occupants and responders – both those who survived and those did not, and to determine the performance of the evacuation system on September 11, 2001.
Fire Service Technologies and Guidelines	8	• Report(s) on Fire Service Technologies and Guidelines to determine the fire service procedures and practices for World Trade Center Buildings 1, 2, and 7, and the fate of emergency response personnel.

Technical Findings and Recommendations	**Reporting Phase**	• Interim and Final Reports on the Technical Findings and Recommendations of the Investigation, including probable technical causes of the disaster.
Dissemination and Deployment of Findings	**Via R&D and DTAP**	• Dissemination and Deployment of Findings via proposed standards and codes changes and participation with industry in their adoption and acceptance into codes and standards.

Attachment 1
Description of Investigation Projects

Project #1: Analysis of Building and Fire Codes and Practices

Purpose: To obtain, review, and analyze applicable building code provisions and project documents and to determine the procedures and practices that were used in the design, construction, and maintenance of the structural, passive fire protection, and emergency access and evacuation systems of World Trade Center Buildings 1, 2, and 7, and to provide input to other investigation projects.

Technical Approach: This project focuses on gathering information that governed the design, construction, and maintenance of the WTC buildings as related to structural and fire safety performance. The major sources of information will be historical records that have been maintained by various entities involved in the design, construction, and maintenance of the structural system, the passive fire protection systems, and the elevator system. Oral history will be obtained from knowledgeable individuals to augment the information in historical records. In addition, building code provisions that governed the project will be compared with code provisions of other major cities that governed tall buildings at the time of design and construction of the WTC buildings. A summary will be prepared of those aspects of the structural, passive fire protection, and elevator systems that may have bearing on the structural performance, occupant evacuation, and loss of lives on September 11, 2001. This project is divided into eight tasks as follows:

Task 1—Review design calculations and project documents. Available documents related to the original design will be reviewed to establish the design loads and methods used to proportion structural components. Special effort will be devoted to documenting the approval process for those aspects of the structural system used in the WTC towers that were not covered by the provisions of the governing code and to document abnormal loads anticipated at the time of the original design of the WTC towers. Available project and as-built drawings (structural, mechanical, architectural) will be obtained for use by other investigation projects.

Task 2—Review building construction. Available construction documentation (such as construction logs, change orders, test and inspection reports) will be reviewed. Significant events encountered during construction (and over the life of the buildings) that may have impacted the performance of the structural, passive fire protection, and elevator systems will be identified and documented. The architectural configuration will be established for the affected stories of WTC 1 and 2 and WTC 7 on September 11 before the attacks.

Task 3—Review passive fire protection features. Those codes and standards that applied to the passive fire protection features of the WTC buildings will be reviewed. This includes documentation of the passive structural fire protection system used in the buildings such as fireproofing, compartmentation, fire stops, and enclosures around egress paths. The structural integrity and fire safety performance of the enclosure shaft for the elevators and stairs will be studied. The maintenance records of the passive fire protection systems will be reviewed. Relevant modifications made to the passive fire protection systems during the service life of the buildings and after the 1993 bombing will be documented.

Task 4—Review emergency access and evacuation systems. Review the design, operation, maintenance, and inspection of the emergency access and evacuation systems in the WTC towers and the condition of these systems at the time of collapse of the buildings. Collect the relevant literature and review existing U.S. and international standards and identify design characteristics and maintenance practices applied to such systems in WTC 1 and 2 that affected their performance on September 11, 2001. Standards and practices for firefighter lifts and FDNY policies will be reviewed to evaluate the potential effectiveness of such technology in improving firefighter effectiveness and reducing firefighter losses.

Task 5—Code comparisons. The New York City, the New York State, and national model codes that were in effect when the buildings were designed will be documented. Specific provisions in those codes will be compared with design requirements for the WTC 1, 2 and 7 buildings. Focus will be on the structural loading criteria and provisions for structural fire protection – including emergency access and evacuation. Code provisions will be compared for high-rise construction in other large cities with those that governed the design of the WTC towers. Current model code provisions will also be compared with those then in effect that governed the design and construction of the WTC buildings.

Task 6—Review maintenance records. A review will be conducted of maintenance and renovation that may have affected the structural system and the passive fire protection system. The objective is to develop the most accurate representation of the structural systems, including the condition of the structural fire protection, as they existed in the portions of the buildings affected by aircraft impacts on September 11, 2001.

Task 7—Document structural modifications following the 1993 bombing. The structural modifications that were made after the 1993 bombing will be reviewed to determine whether they may have affected the structural system of the WTC buildings.

Task 8—Report preparation. The results of this project will be synthesized into a chapter to describe the design, construction, and maintenance of and modifications to the WTC buildings. The structural configuration, passive fire protection systems, and elevator system at the time of the attack will be described. In addition, the internal condition of the architectural and mechanical systems will be documented with input from other investigation projects. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion[1]:

1. Interim report that documents the design basis for the WTC buildings and describes the process by which the innovative structural system was approved and the abnormal loads from aircraft impact anticipated in the original design of the WTC towers (6 months).
2. Interim report that summarizes pertinent construction data for the WTC buildings (9 months).
3. Interim report that documents code provisions related to high-rise construction and structural fire safety (9 months).
4. Interim report that documents maintenance and modifications that may have affected the structural and passive fire protection systems within the affected regions of the buildings. This includes modifications resulting from the 1993 bombing (10 months).

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[1] Estimated time-to-completion is from start of investigation.

5. Interim report on regulations and practices related to the passive fire protection features systems in the buildings (9 months).

6. Interim report on the design, operation, maintenance, and performance of emergency access and evacuation systems in the WTC towers (6 months).

7. Draft chapter for final report that describes the design, construction, and maintenance of and modifications to the structural, passive fire protection, and elevator systems, and that documents the probable conditions of the buildings at the time of the attacks on September 11, 2001 (16 months).

Project #2: Baseline Structural Performance and Aircraft Impact Damage Prediction

Purpose: To evaluate the role of the structural system design and the abnormal loads from aircraft impact on the collapse of the WTC towers by: (1) developing reference structural, mechanical, and architectural (SMA) models of the WTC towers, (2) establishing baseline performance of each of the towers under design loading conditions (especially gravity and wind), (3) estimating probable damage to the SMA systems of the towers due to aircraft impact, (4) comparing differences between anticipated and actual abnormal loads posed by aircraft impact, and (5) estimating the structural reserve capacities of the towers to accommodate abnormal loads under service conditions and after aircraft impact.

Technical Approach: This project focuses on establishing the baseline performance of the WTC towers, evaluating the effect of the aircraft impact on their response, and estimating the probable damage to the structural, mechanical, and architectural (SMA) systems. In addition, a comparison will be conducted between the response and damage to the towers due to the actual impact of the Boeing 767 aircraft and the abnormal load condition of a Boeing 707 aircraft impact anticipated at the time of the original design. This project will also evaluate the reserve capacities of the towers immediately after impact. Since the structural design of the towers included many innovations such as the use of perimeter tube system, prefabricated exterior column elements, wind tunnel testing, and damping devices in the floor system, this project will establish the baseline performance of the structural system under design gravity and wind loads. This project is divided into six tasks as follows:

Task 1—Develop SMA models of the two towers. The structural plans for the two towers will be studied to select appropriate structural modeling strategies for the different response analysis objectives. The models will need to recognize the special features of the structural system such as the floor diaphragms consisting of open-web steel trussed joists and composite slab, the exterior prefabricated column elements, and the variety of connection details used in the towers. The models will have levels of complexity ranging from frame elements representing the entire structural system to detailed finite element meshes of shell elements of the structures in the vicinity of the level of impact. These models – after third-party review – will be used for various phases of the investigation dealing with the structural performance of the towers. To simplify modeling efforts, a database for the two towers that includes geometries, dimensions, and material properties of the various structural members will be developed. CAD models will be developed to represent both mechanical and architectural systems. Mechanical models will include HVAC, elevators, and water supply systems while architectural models will include interior layouts, stairways, fire suppression systems, etc.

Task 2—Analyze the structural models of the towers under design loading conditions to establish the baseline performance, including estimation of structural reserve capacities and the diaphragm action provided by the floor system.

Task 3—Simulate the aircraft crash into the towers to estimate the extent of damage to SMA systems. The analysis of the aircraft crash will be performed at various levels of complexity ranging from energy and momentum conservation calculations to state-of-the-art, three-dimensional, and large-deflection finite element analyses of both the aircraft and the towers. The simulations will account for the speed, direction, and mass and stiffness distribution of the aircraft. This task will use WTC tower steel properties, including high strain rate properties, obtained from the project on Forensic Analysis of Structural Steel. The primary purpose of this task is to provide estimates of the probable damage to structural systems – including floors and exterior tube and interior core columns, and the load redistribution provided by the outrigger truss system – rather than the damage done to the aircraft. Therefore, the level of complexity of the aircraft model will be selected to achieve this analysis objective. Multiple simulations of the impact accounting for the various sources of uncertainty will be used to provide bounds for the extent of damage to mechanical and architectural systems. Structural models of the damaged towers will be developed for use in subsequent analyses.

Task 4—Analyze the towers under anticipated abnormal loads due to the impact of a Boeing 707, flying at the speed assumed when the towers were designed, to estimate the extent of damage and the reserve capacity after impact. The results of this analysis will be compared with information that may be available on the damage estimated in the original design of the towers. A comparison between the results of tasks 3 and 4 will be conducted to compare the differences in the response and damage between the anticipated and actual abnormal loads posed by aircraft impact.

Task 5—Determine the response of the towers immediately after the impact. The focus of this task is to quantify the structural reserve capacity (or margin of safety against collapse) under existing service loads following the loss of exterior and core columns and floors due to the aircraft impact. This task will help to determine how the towers responded and the mechanism by which they remained standing immediately after the aircraft crashes and prior to collapse, and specifically to evaluate how close they were to collapse immediately after the crashes.

Task 6—Report preparation. The results of this project will be synthesized into a chapter to describe the baseline structural performance of the towers under design conditions, estimates of damage to the SMA systems due to aircraft impact, and the reserve capacity of the structural components under design and abnormal loads and subsequent to damage by aircraft impact. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion:

1. First-order estimate of the damage to the towers. Models for Boeing 767 and 707 aircraft obtained (4 months).
2. Reference structural, architectural, and mechanical models of the towers. Third-party review of SMA models (6 months).
3. Interim report on estimation of the local and global response of the towers to aircraft impact including damage to structural, architectural, and mechanical systems (12 months).
4. Reference structural models of the damaged towers (13 months).
5. Interim report on baseline performance of the two towers under gravity and wind loads (14 months).
6. Response analysis of the WTC towers to actual and anticipated abnormal loads from aircraft impact (15 months).
7. Interim report on estimation of the structural reserve capacity of the towers under design and abnormal loads as well as immediately after aircraft impact (17 months).

8. Draft chapter for final report that describes the baseline structural performance of the towers under design conditions, and estimates damage to the SMA systems due to aircraft impact and the reserve capacity of the components of the tower structures damaged by aircraft impact (18 months).

Project #3: Forensic Analysis of Structural Steel

Purpose: To analyze structural steel available from WTC Buildings 1, 2, and 7 to determine properties and quality of the metal, weldments, and connections, and provide data for other investigation projects.

Technical Approach: This project is divided into six tasks as follows:

Task 1—The physical evidence (structural steel components and connections) and other data, such as specifications for the steel, which are available, will be collected and cataloged. This information will identify the location of steel pieces within the buildings and determine what steel and properties were specified.

Task 2—Failure mechanisms and damage will be documented based on visual observations of recovered steel, especially focused on available columns, connectors, and floor trusses. The cause of extreme erosion seen on some parts of the steel columns will be studied.

Task 3—The metallurgical and mechanical properties of the steel, weldments, and connections, including temperature dependence of properties, will be determined. The grades of steel in the exterior columns will be identified, as well as those in core columns (if available), welds, spandrels, trusses, truss seats, and fasteners. The identification will include composition, microstructure, mechanical, and impact properties. This project will provide steel property data, including models of elevated temperature behavior for relevant steels, to estimate damage to the towers from aircraft impact, evaluate structural fire response, and study the initiation and propagation of structural collapse.

Task 4—Steel properties will be correlated with the material properties specified for construction of the buildings. An assessment of the quality of the steel compared with that specified for the construction will be made.

Task 5—The steel will be analyzed metallographically to estimate maximum temperatures reached. It is recognized that high temperature exposure before the collapse may be difficult to distinguish from exposure during post-collapse fires.

Task 6—Report preparation. The results of this phase of the investigation will be synthesized into a chapter to describe the results of the forensic analysis of the structural steel available from the WTC towers. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion:

1. Catalog of available structural steel and relevant specifications (4 months).
2. Documentation of failure mechanisms and damage from visual observations (4 months).
3. Interim reports on the metallurgical and mechanical properties of the steel and connections, including temperature dependence of properties.
   a. Identification of steel in the exterior columns, core columns (if available), welds, spandrels, trusses, truss seats, and fasteners based on composition, microstructure,

room temperature tensile properties, and impact properties (partial results in 4 months, complete in 12 months).

   b. *Data to support airplane impact modeling studies* – high strain rate mechanical properties and impact properties of columns, spandrels, bolts, and welds on columns (partial in 4 months, complete in 14 months).
   c. *Data to support models of steel frame performance in fire* – creep and high temperature tensile properties of columns, bolts on columns, trusses, truss seats, and bolts or welds associated with truss seats (partial results in 4 months, complete in 12 months).
   d. *Data to support models of steel during collapse* – high strain rate room temperature tensile properties of truss seats and associated bolts and welds (partial results in 5 months, complete in 16 months).
   e. Models of elevated temperature deformation as a function of load, temperature and time history for relevant steels (some steels in 6 months, complete in 16 months).

4. Estimation of maximum temperatures reached by collected structural steel (complete in 12 months).

5. Database of microstructural changes with temperature in the various classes of steels for future use by building fire community (16 months).

6. Comparison of steel properties to applicable material specifications (12 months).

7. Draft of chapter for final report that describes the results of the forensic analysis of the structural steel available from the WTC towers (18 months).

Project #4: Investigation of Active Fire Protection Systems

Purpose: To document and evaluate the performance of the installed active fire protection systems in the World Trade Center Buildings 1, 2, and 7 on September 11, 2001 and assess their role in fire spread, emergency response, and the fate of occupants and responders.

Technical Approach: This project is divided into six tasks as follows:

Task 1—Information available from the Port Authority and its contractors and consultants will be used to document previous fire events in WTC Buildings 1, 2, and 7.

Task 2—The active fire protection systems – including the installed sprinkler, manual suppression, fire alarm, and smoke management systems in WTC 1, 2, and 7 – will be documented.

Task 3—The design of the active fire protection systems will be analyzed relative to applicable building codes and standards at the time of installation. The maintenance, modifications, and inspection records for these systems will be reviewed. Modifications made after the 1993 bombing incident will be documented. The design requirements, including capacity and redundancies, will be compared with those in other major cities.

Task 4—A comprehensive set of questions will be developed to collect information from building operators, first responders, building occupants, and families of victims on the operation of and damage to the fire safety systems on September 11, 2001. These questions will be included in the information gathering that will be coordinated with other investigation projects, in particular the efforts related to fire service technologies and guidelines, building and fire codes, and occupant behavior and egress.

Task 5—The information collected in tasks 1-4 will be reviewed and analyzed by a panel of fire protection engineers with expertise in the operation and capabilities of active fire protection systems to establish the facts regarding the performance of these systems in WTC 1, 2, and 7 on September 11, 2001. NIST will interpret and analyze these facts and document its findings. This analysis will review the role and effectiveness of active fire protection systems in large compartment fires.

Task 6—Report preparation. The results of this project will be synthesized into a chapter to describe the installed active fire protection systems in WTC 1, 2, and 7, and the performance of these systems on September 11, 2001. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion:

1. Collection of information on previous fires in WTC Buildings 1, 2, and 7 (3 months).
2. Comprehensive set of questions developed to collect information on operation of and damage to fire safety systems on September 11, 2001 (3 months).
3. Interim report on design, installation, and maintenance of and modifications to active fire protection systems present in WTC 1, 2, and 7, and compare with applicable codes in New York City and other major cities (5 months).

4. Interim information on instructions and information provided by the fire alarm system to the building occupants and fire service and the operation of the smoke management systems (6 months).
5. Synthesis of collected information that will be used to establish the facts and analyze the performance of the active fire protection systems (12 months).
6. Draft of chapter for final report that describes the installed active fire protection systems in WTC 1, 2, and 7, and evaluates the performance of these systems on September 11, 2001 (18 months).

Project #5: Prediction of Thermal and Tenability Environment

Purpose: Reconstruct, with assessed confidence/uncertainty limits, the time-evolving temperature, thermal radiation, and smoke fields in World Trade Center Buildings 1, 2, and 7 for use in evaluating the behavior and fate of occupants and responders and the structural performance of the buildings.

Technical Approach: This project is divided into seven tasks as follows:

Task 1—Guidance on the initial conditions for modeling the fires, the rates of fire spread, the floors on which the structural collapses appear to have begun, etc., will be developed through the acquisition of available and relevant photographic and video images of damage to the three buildings, review of accounts from occupants and responders, and the cataloging and analysis of such images and accounts.

Task 2—The types of combustibles and estimates of the mass loading will be characterized by gathering data on the internal construction materials, furnishings and contents. The types of combustibles and estimates of mass loading will be compared with data from prior surveys of similar occupancies. Other fuel sources in WTC 7 will be identified and documented. The extent of the dispersed aviation fuel in WTC 1 and 2 will be estimated based on input from the Baseline Structural Performance and Aircraft Impact Damage Prediction project.

Task 3—Existing data on the fire performance of floor, wall, and ceiling systems will be compiled, complemented by additional measurements as needed, to determine air access for the combustion, to identify fire paths for intercompartment fire spread, and to identify those paths that were capable of contributing to the collapse of the buildings.

Task 4—The thermal properties of the structural insulation systems and the effects of vibration, impact, and shock on their thermal performance will be determined to estimate the thermal environment on the outside of the protected structural members. Also included will be indication of whether chemical interaction between the insulation materials and the steel at elevated temperatures could contribute to degradation of structural performance in the time available.

Task 5—The capabilities of NIST's Fire Dynamics Simulator (FDS) will be extended, using knowledge gained from the previous tasks, to reconstruct the temperature, thermal radiation, and smoke fields within the three buildings as a function of time and location. Reduced-scale experiments will be used to guide and evaluate the accuracy of key FDS sub-models.

Task 6—FDS will be used to simulate fully involved fires in the three buildings, with and without the initial damage from the aircraft or incident debris, for evaluating the extent to which that damage affected the thermal environment experienced by the structure. Parameters in the re-creation of the fires will enable estimation of the roles of jet fuel and building contents, ventilation system, compartment damage, pressurized core, and fire protection system on growth and spread of fire. Uncertainty and confidence intervals will be estimated for the accuracy of the reconstructions. The effectiveness of compartmentation in controlling fire spread in these buildings on September 11, 2001 will be analyzed.

Task 7— Report preparation. The results of this project will be synthesized into a chapter to describe the time-evolving temperature, radiation, and smoke fields in WTC 1, 2, and 7 and the effectiveness of compartmentation in controlling fire spread in these buildings on September 11,

2001. All experiments, model assumptions and operations, and reconstructions will be documented. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion:

1. First analysis of photographic and video images of damage to WTC buildings 1, 2, and 7 (3 months).

2. Compilation of data on construction materials and systems, furnishings and contents, and other fuel loads (4 months).

3. Evaluation of the thermal performance of structural insulation system(s) (8 months).

4. Completion of experiments to guide FDS sub-model development (10 months).

5. First prediction of the fire dynamics in one of the WTC towers (12 months).

6. Evaluation of pathways for fire ventilation and for compartment-to-compartment fire growth in the three buildings (14 months).

7. Completion of reduced-scale demonstration experiments (15 months).

8. Final predictions, with uncertainties, of the time-varying temperature, thermal radiation and smoke fields in WTC 1, 2, and 7 (16 months).

9. Draft chapter for final report that describes the time-evolving temperature, radiation, and smoke fields in WTC 1, 2, and 7 and the effectiveness of compartmentation in controlling fire spread in these buildings on September 11, 2001 (18 months).

Project #6: **Structural Fire Response and Collapse**

Purpose: To determine the response of structural components and systems to the fire environment in the World Trade Center Buildings 1, 2, and 7, and to identify probable structural collapse mechanisms.

Technical Approach: This project is divided into seven tasks as follows:

Task 1—Evaluate the response of floor and column systems under fire conditions. The following sub-tasks will be performed:

a. Develop structural model of floor truss and slab system including supports (i.e., connections to columns). Obtain information from project on Baseline Structural Performance and Aircraft Impact Damage Prediction.
b. Develop structural model of both interior (core) and exterior column system for the floors of interest. Obtain information from project on Baseline Structural Performance and Aircraft Impact Damage Prediction.
c. Obtain thermal environment predictions. Consider both standard fires (e.g., ASTM E-119 and ASTM E-1529) and real fires based on fire dynamics simulations.
d. Obtain thermal and mechanical properties of steel truss and connections as well as steel columns sections at elevated temperatures.
e. Obtain thermal insulation properties of spray-on fire proofing.
f. Estimate, using transient thermal analysis, the time-temperature relationship for the floor truss and column systems. Consider both unprotected and protected steel.
g. Evaluate, using thermal-mechanical analysis, the time-dependent structural response of the floor truss system, including support reactions (connection forces), and the column system.

Task 2—Evaluate the response of the WTC towers without and with aircraft impact damage under fire conditions. The following sub-tasks will be performed:

a. Develop structural model of floors of interest (location and number of floors to be determined) to evaluate the response of the WTC towers without aircraft impact. Obtain information from project on Baseline Structural Performance and Aircraft Impact Damage Prediction.
b. Develop structural model (including aircraft damage) of floors of interest (impact floors and floors above that are involved in fire). Obtain information from project on Baseline Structural Performance and Aircraft Impact Damage Prediction.
c. Obtain thermal environment predictions. Consider both standard fires (e.g., ASTM E-119 and ASTM E-1529) and real fires based on fire dynamics simulations.
d. Estimate, using transient thermal analysis, the time-temperature relationship for the structural components. Consider both unprotected and protected steel.
e. Evaluate, using thermal-mechanical analysis, the time-dependent structural response of the floors of interest.
f. Identify components critical to collapse initiation.

Task 3—Conduct tests of structural components and systems under fire conditions. In the course of the investigation, it may be necessary to re-create the predicted thermal environment and structural response of components such as floor truss seat connections, floor truss assemblies, and exterior prefabricated column-spandrel elements. Such tests would be used to validate analytical models and to provide response data that are otherwise unavailable.

Task 4—Evaluate failure hypotheses for the WTC towers. The following sub-tasks will be performed:

a. Identify candidate hypotheses for initiation and propagation of collapse.
b. Evaluate hypotheses for collapse initiation and propagation, including the role played by floor diaphragms and connections.
c. Estimate uncertainty and confidence intervals for probable collapse initiation and propagation mechanisms.
d. Identify most probable collapse mechanism(s).

Task 5—Report on the performance of open-web steel trussed joists in fire. The past performance of open-web steel joist systems in fire will be investigated. This study will include fire incident reports, insurance investigation reports, etc. Test reports (ASTM E119 or others) of steel joist systems in fire will be obtained and evaluated. Data obtained both domestically and, where possible, internationally will be included in the investigation. The results of this review will be compared with the floor truss system used in the WTC towers.

Task 6—Predict the response of WTC Building 7 under fire conditions. The following sub-tasks will be performed:

a. Develop model of structural system.
b. Obtain fuel loads for various tenants and internal building operating systems (e.g., power generation) from project on Prediction of Thermal and Tenability Environment.
c. Obtain thermal environment predictions. Consider both standard fires (e.g., ASTM E-119 and ASTM E-1529) and real fires based on fire dynamics simulations.
d. Obtain properties of steel at elevated temperatures from project on Forensic Analysis of Structural Steel.
e. Estimate, using transient thermal analysis, the time-temperature relationship for the structural system.
f. Evaluate, using thermal-mechanical analysis, the time-dependent structural response of the structural system including transfer girder system.
g. Identify most probable collapse mechanism.

Task 7— Report preparation. The results of this project will be synthesized into a chapter to describe the response of structural components and systems to the fire environment in the World Trade Center Buildings 1, 2, and 7, and to identify probable structural collapse mechanisms. The performance of open-web steel trussed joist systems in fire will be documented. In addition, the role of pivotal components such as floor diaphragms, connections, and transfer girders in collapse initiation will be documented. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion:

1. Evaluation of the response of floor system under fire conditions (9 months).

2. Evaluation of the response of column system under fire conditions (12 months).

3. Evaluation of the response of the WTC towers with no aircraft impact under fire conditions (16 months).

4. Evaluation of the response of the WTC towers with aircraft impact under fire conditions (17 months).

5. Report on the performance of open-web steel trussed joist systems in fire (6 months).
6. Completion of design, construction, and testing of critical components (16 months).
7. Evaluation of the response of WTC Building 7 under fire conditions (17 months).
8. Draft chapter for final report that describes the response of structural components and systems to the fire environment in the WTC 1, 2, and 7, and the probable structural collapse mechanisms. The performance of open-web steel trussed joist systems in fire and the role of pivotal components such as floor diaphragms, connections, and transfer girders in collapse initiation will be documented (18 months).

Project #7: Occupant Behavior, Egress, and Emergency Communications

Purpose: To determine the behavior and fate of occupants and responders – both those who survived and those who did not – by collecting and analyzing information on occupant behavior, human factors, egress, and emergency communications in World Trade Center Buildings 1, 2, and 7, and evaluating the performance of the evacuation system on September 11, 2001.

Technical Approach: This project is divided into six tasks as follows:

Task 1— Baseline information on the evacuation of the WTC buildings on September 11, 2001 will be developed through a comprehensive, systems-oriented, and interdisciplinary data collection effort focused on occupant behavior, human factors, egress, and emergency communications (including instructions given, interpretation of instructions, and response to instructions). This will involve the collection of new data from people affected by the WTC attacks (e.g. building occupants and first responders via direct accounts from survivors and families of victims), especially those who had to evacuate the buildings. Experts in human behavior and statistical sampling will be used to develop a data acquisition strategy that considers various data collection methods such as interviews and surveys. Inputs and suggestions will be obtained from groups with an interest in the content of the data collection effort. Additionally, written accounts, transcripts of (emergency) communications, published accounts, and other sources of egress related information will be obtained, in coordination with other data collection efforts for the investigation.

Task 2—Archival records from prior WTC evacuation incidents (e.g., 1977 blackout, 1980 bomb scare, 1990 power outage, and 1993 bombing) and practice evacuations will be collected. These records will be compared and contrasted with the September 11th incident evacuation. Changes made to the evacuation procedures following the earlier incidents will be evaluated in the context of the experience on September 11, 2001.

Task 3—Pre-event data will be recorded for WTC Buildings 1, 2, and 7. This information includes, but is not limited to, physical aspects of building egress components, such as stairs (width, number, location, vertical continuity), evacuation lighting, back-up power, elevators (number, operational before and after impact, role in evacuation), and active fire protection systems (sprinklers, manual suppression, fire alarms, smoke control). Building plans, emergency plans, type and frequency of evacuation drills, occupancy level and distribution on the morning of September 11th, and communications will also constitute pre-event data. This information will provide a baseline for evaluating the performance of the egress system.

Task 4—The information collected in task 1 will be stored in a database. Additionally, information from third-party sources, such as television interviews and newspaper articles, as well as other relevant published material will be analyzed, examined, and assembled in the database.

Task 5—The data will be analyzed to study the movement of people during the evacuations, decision-making and situation awareness, and issues concerning persons with disabilities. A timeline of the evacuation will be developed using the results of these analyses together with other data sources. This timeline will be compared with the timeline of the structural response, the development of the interior conditions (fire and smoke), as well as activation of the active fire protection systems. The characteristics of the WTC evacuation designs and protocols will be evaluated, including the performance of stairs and elevators, emergency communications, and building tenability. The designs will also be compared with building code requirements and practices for tall buildings in other major cities worldwide. The observed evacuation data will be compared with predictions obtained using alternate egress models to better understand occupant behavior and identify needed improvements to existing egress models. In addition, the evacuation experience on September 11, 2001 will be compared with previous evacuation incidents in these buildings. The results of the analyses will be reviewed in the context of occupant protection practices for tall buildings, including the consideration of full evacuation and phased evacuation strategies.

Task 6— Report preparation. The results of this project will be synthesized into a chapter to describe the occupant behavior, egress, and emergency communications in WTC 1, 2, and 7, and the performance of the evacuation system on September 11, 2001. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion:

1. Completion of data collection design strategy (4 months).

2. Collection of archival data and pre-event data (4 months).

3. Completion of data collection effort and database development (9 months).

4. Completion of analysis of occupant behavior, egress, and emergency communications as defined in task 5 (17 months).

5. Draft chapter for final report that describes the occupant behavior, egress, and emergency communications in WTC 1, 2, and 7 and the performance of the evacuation system on September 11, 2001 (18 months).

Project #8: Fire Service Technologies and Guidelines

Purpose: To determine fire service procedures and practices for World Trade Center Buildings 1, 2, and 7, and the fate of emergency response personnel by (1) documenting the performance of first responders and their equipment on September 11, 2001, (2) identifying the effects of available alternatives related to emergency first responder technology, training, and operational procedures, and (3) identifying R&D needs in support of their capability to protect the public, first responders, and vital physical infrastructure during extreme events.

Technical Approach: This project is divided into four tasks as follows:

Task 1—Emergency response data will be collected and analyzed to document first responder fatality, command and control procedures and performance, and written records (e.g., dispatch logs, recorded radio communications, run logs from surviving responding units, 911 records, data recorded by Port Authority operations, and any other documents identified as critical to the investigation). This will include operations and function of communications systems, on-site emergency information systems, fire alarm panels, elevator control panels, standpipes, fire hoses, and other pre-positioned emergency equipment, etc. Oral history data will be collected from surviving first responders, witnesses, and those in control of emergency operations, in coordination with other data collection efforts for the investigation. A panel of emergency responder experts will be convened to review the data and conduct a fact-based analysis of the emergency response on September 11, 2001.

Task 2—NIST will interpret the factual analysis to determine the effect on responder successes of factors such as:

- pre-planning, training, and standard operating procedures at the time of the incident;
- the influence that building design (e.g., height, stairways, elevators, smoke control systems), the impact of systems failures (e.g., water supply, sprinklers, standpipes), and command and control procedures had on life saving operations and safety of rescue personnel;
- barriers to efficient performance in and surrounding buildings and strategies employed to overcome barriers;
- how operational procedures, including command and control, may have been altered to manage the incident;
- the effectiveness of fire and emergency response protocols for tall buildings;
- the ability to fight large fires on the upper floors of tall buildings;
- the impact that the 1993 bombing of the WTC had on codes and standards that affected first responders in tall buildings (what recommendations were made and what changes were made in training, tactics, and operational procedures); and
- the resources available for initial situation assessment and incident management, and practices for predicting the possibility of structural collapse.

Task 3—The emergency response practices used in New York City will be compared with practices used in other major cities to evaluate the effectiveness of the responders on September 11, 2001.

Task 4— Report preparation. The results of this project will be synthesized into a chapter to describe: the performance of first responders and their equipment on September 11, 2001; identify the effects of available alternatives related to emergency first responder technology, training, and operational procedures; and identify R&D needs in support of their capability to protect the public, first responders, and vital physical infrastructure during extreme events. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion:

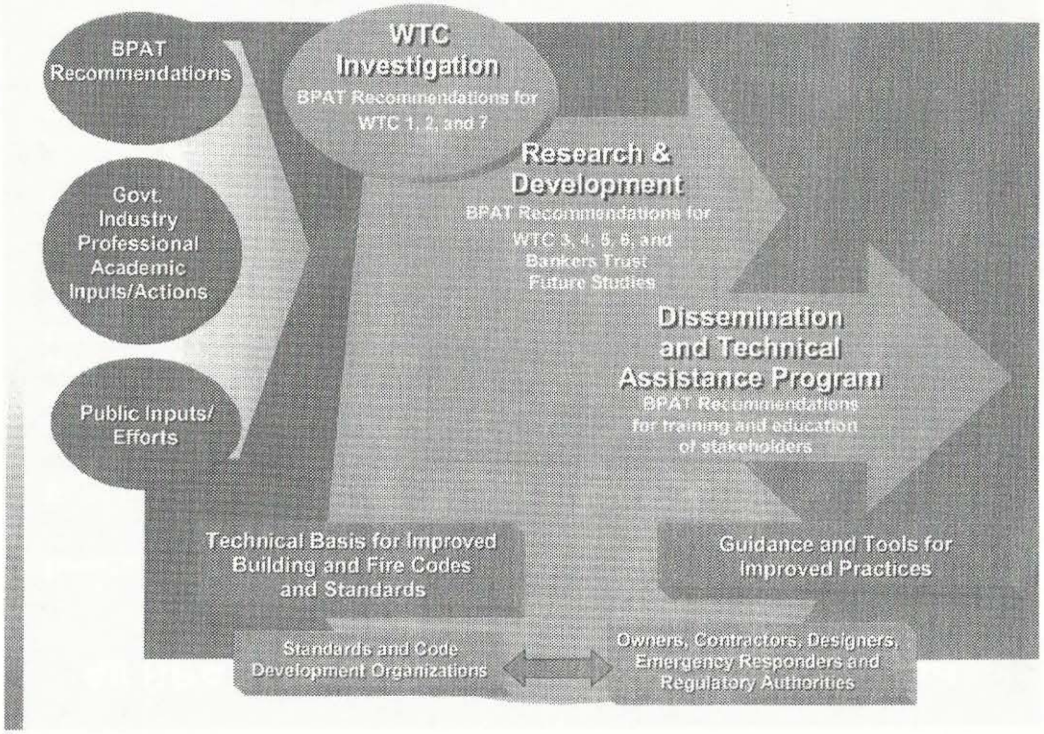
1. Documentation of the activities of emergency responders, including their injuries and fatalities (8 months).

2. Evaluation of the degree of success of responders in preserving life and property and the factors that limited that success (14 months).

3. Identification of the key factors where R&D may improve the capability of responders to protect the public, first responders, and vital physical infrastructure during extreme events (16 months).

4. Draft chapter for final report that describes the performance of first responders and their equipment; identify the effects of available alternatives related to emergency first responder technology, training, and operational procedures; and identify R&D needs in support of their capability to protect the public, first responders, and vital physical infrastructure during extreme events (18 months).

Proposed NIST Response Plan



BPAT Recommendations

Govt.
Industry
Professional
Academic
Inputs/Actions

Public Inputs/
Efforts

WTC Investigation
BPAT Recommendations for WTC 1, 2, and 7

Research & Development
BPAT Recommendations for WTC 3, 4, 5, 6, and Bankers Trust
Future Studies

Dissemination and Technical Assistance Program
BPAT Recommendations for training and education of stakeholders

Technical Basis for Improved Building and Fire Codes and Standards

Guidance and Tools for Improved Practices

Standards and Code Development Organizations

Owners, Contractors, Designers, Emergency Responders and Regulatory Authorities

All BPAT Recommendations to be Addressed

NIST Response Plan

Investigation ⟹ R&D ⟹ Dissemination & Technical Assistance

Building Chapters

WTC 1 & 2. impact, fire, floor systems, structural, materials, arrest collapse…

WTC 7. Initial damage, fuels, fire-structure interactions, collapse mechanisms, axial capacity, level of fire resistance for key members

WTC 3. progressive collapse.

WTC4,5,6. Performance of connections in fire, structural performance in overload.

Bankers Trust. How collapse was halted.

Peripheral buildings. Software verification.

Future Study Chapter

Building Evacuation
Emergency Personnel
Archival information

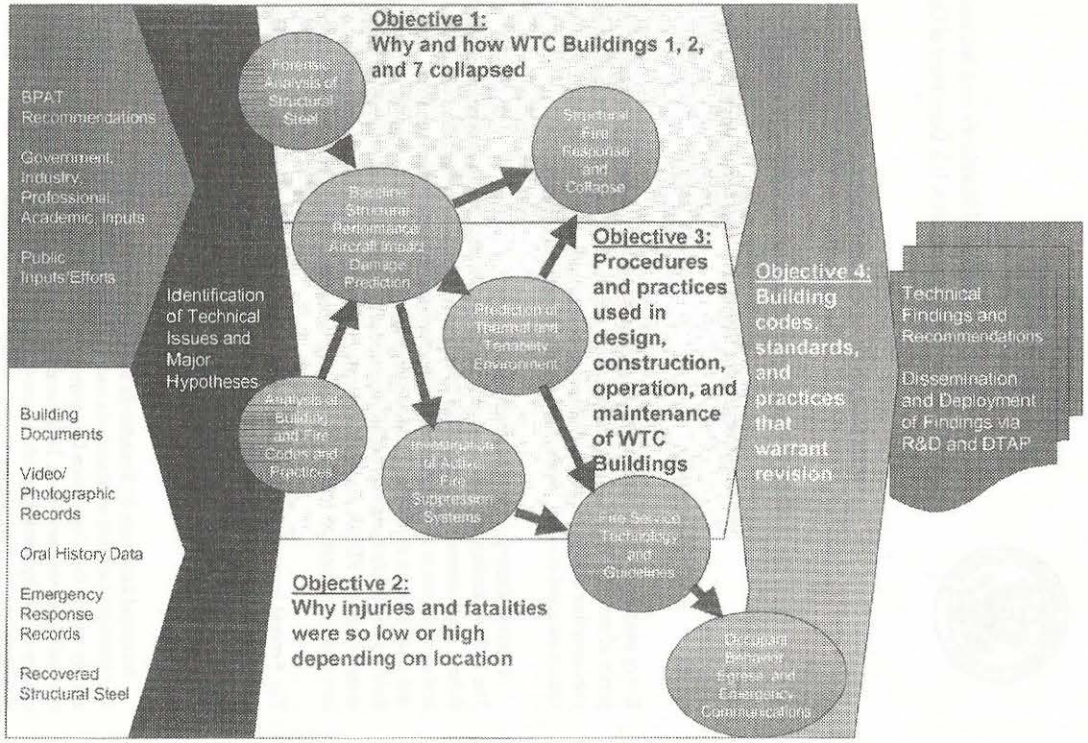
Fire structural interactions.

Fire and Structural professions in design.

Fire Protection Engineering Discipline.

Education of stakeholders
Study process
Response to disasters.
SEONY Response Plan

NIST WTC Investigation Plan


Forensic Analysis of Structural Steel
Baseline Structural Performance Aircraft Impact Damage Prediction
Structural Fire Response and Collapse
Prediction of Thermal and Tenability Environment
Analysis of Building and Fire Codes and Practices
Investigation of Active Fire Suppression Systems
Fire Service Technology and Guidelines
Occupant Behavior, Egress, and Emergency Communications

BPAT Recommendations

Government, Industry, Professional, Academic, Inputs

Public Inputs/Efforts

Building Documents

Video/ Photographic Records

Oral History Data

Emergency Response Records

Recovered Structural Steel

Identification of Technical Issues and Major Hypotheses

Objective 1:
Why and how WTC Buildings 1, 2, and 7 collapsed

Objective 2:
Why injuries and fatalities were so low or high depending on location

Objective 3:
Procedures and practices used in design, construction, operation, and maintenance of WTC Buildings

Objective 4:
Building codes, standards, and practices that warrant revision

Technical Findings and Recommendations

Dissemination and Deployment of Findings via R&D and DTAP

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

MEMORANDUM OF UNDERSTANDING
Between the

Federal Emergency Management Agency (FEMA)
and the
National Institute of Standards and Technology (NIST)

I. BACKGROUND

Every year, millions of Americans face disaster, and its terrifying consequences. Natural perils of extreme winds, fires, earthquakes, floods, along with failures in the nation's infrastructure and terrorism may threaten communities. FEMA and NIST are working to reduce national disaster losses and enhance homeland security.

Federal Emergency Management Agency

The Federal Emergency Management Agency ("FEMA") is an independent agency of the federal government reporting to the President. FEMA's vision is "A Nation Prepared" and our mission is to lead America to prepare for, minimize damage from, respond to, and recover from disasters. FEMA encourages communities across the country to assess their risk, identify their vulnerabilities, and take steps to prevent disaster damage before disaster strikes. FEMA disseminates information on the latest research, technology and mitigation practices to local communities, where this information is needed most.

The Federal Insurance and Mitigation Administration (FIMA) works to reduce loss of life and property and to protect the nation's critical infrastructure from all types of hazards, through a comprehensive, risk-based emergency management program of mitigation that enhances disaster preparedness, response, and recovery.

National Institute of Standards and Technology

The National Institute of Standards and Technology ("NIST") is a non-regulatory, federal agency within the Commerce Department's Technology Administration. Through research and other activities, NIST strengthens the nation's economy and improves the quality of life by working with industry to develop and promote technology, measurements and standards.

NIST's Building and Fire Research Laboratory ("BFRL") partners with other public and private sector bodies in research, development, demonstration and deployment programs in four strategic areas: advanced construction systems and processes, high performance building materials, building performance enhancement, and fire and disaster loss reduction.

Specifically, BFRL

- Conducts problem-focused research and development to enable innovation by removing technical barriers, evaluating advanced technologies, and providing the technical basis for performance standards, codes, and practices.
- Develops advanced measurement, modeling, and simulation tools to measure and predict the performance of buildings and critical physical infrastructure under extreme conditions (e.g., earthquakes, extreme winds, fires, blast, impact, and chemical/biological hazards).
- Conducts disaster and failure investigations to study performance, derive lessons learned, create new technical and/or scientific knowledge, and develop the technical basis and recommendations for improved building and fire standards, codes, and practices.

NIST's other laboratories offer a unique combination of additional resources for support of and synergy with FEMA's mission programs.

II. PURPOSE

This Memorandum of Understanding ("MOU") establishes a framework for NIST to serve as a research resource for FEMA in the areas of fire, disaster prevention, and homeland security and serves to improve and enhance the effectiveness of cooperation between FEMA and NIST. Its purposes are to (1) further the reduction of loss of life and property and protect the nation's buildings and infrastructure from all types of hazards, (2) aid the development of technology and methods to evaluate equipment for use by the Nation's first responder and emergency management communities, and (3) to assist FEMA with scientific and technological services in disaster investigations, recovery planning and support technologies.

III. AGREEMENT OF COOPERATION

FEMA and NIST recognize that their missions in fire, disaster prevention, and man-made disaster events are highly complementary and that it is in the public interest to exploit that synergy. FEMA serves the first responder and emergency management communities by disseminating critical technology and practices. NIST has expertise to develop, validate, and demonstrate technologies, measurement and evaluation methods, and best practices.

NIST also works closely with industry and university experts and organizations in carrying out its work.

NIST will provide scientific and technical assistance to FEMA in areas of NIST competence to the extent possible within the limitations of NIST's research priorities and available resources. In addition, FEMA may call on NIST as a research and technical resource when needed for technology assessment and development. This in no way bars FEMA from obtaining such support in a competitive process from other sources, nor does it bar NIST from providing services to, or obtaining such support in a competitive process from, other sources.

The Administrator of FIMA shall represent FEMA for matters pertaining to this MOU. Working through the Administrator of FIMA, other FEMA elements may call upon assistance from NIST under this MOU.

IV. FEMA – NIST COORDINATION

FEMA and NIST agree to develop and implement a coordinated annual process to plan, prioritize, select, and fund projects of mutual interest in fire, disaster prevention, and homeland security, and in equipment evaluation for first responders and emergency management agencies.

FEMA and NIST agree to establish a quick deployment mechanism that may be activated when both the Administrator of FIMA and the Director of NIST determine a need for a NIST response to extreme events. FEMA and NIST agree to develop and sign, within 60 days of the date of this agreement, an operational protocol for the quick deployment mechanism. The protocol will define the NIST role and readiness requirements. This provision does not preclude either FEMA or NIST from responding to extreme events independently under their respective authorities.

FEMA and NIST agree that projects may involve cooperation with and/or participation of other agencies, industries and university experts.

FEMA and NIST agree that each agency will designate an Agency Point-of-Contact for carrying out this MOU with subsequent Points-of Contact identified for each addendum to this MOU. These individuals shall be named within 60 days of the signing of this MOU.

The Administrator of FIMA and the Director of NIST, or their designees, will meet on a semi-annual basis to review progress and provide general policy direction in implementing this agreement.

V. AUTHORITIES

Nothing herein is intended to conflict with current FEMA or NIST authorities or directives or to supercede the provisions of other agreements between FEMA and NIST. If any terms of this MOU are inconsistent with existing authorities or directives of either of the Agencies entering into this MOU, those portions of this MOU that are determined to be inconsistent shall be invalid; the remaining terms and conditions shall remain in full force and effect.

VI. IMPLEMENTATION

Activities under this MOU shall be implemented through addenda that describe specific activities, programs, projects, authorities, and financial arrangements. These addenda shall be incorporated into this agreement in the future based upon mutual agreement between FEMA and NIST.

This MOU is effective March 29, 2002.

VII. AMENDMENT AND TERMINATION

This MOU shall be reviewed annually, and it may be amended at any time by the consent of both parties. Addition of projects described in whole as a signed Addendum may be added at any time, as appropriate and practical, by mutual consent. The Director of NIST and the Administrator of FIMA agree that either party may terminate this MOU 60 days after notifying the other party in writing.

Nothing in this MOU shall be construed as constituting an obligation of, or obligating, appropriations or funds of a party to this MOU.

APPROVED:

Arden L Bement Jr.
Arden L. Bement, Jr, Director
National Institute of Standards and Technology

March 29, 2002
(Date)

Robert Shea Jr.
Robert F. Shea, Jr, Acting Administrator
Federal Insurance and Mitigation Administration
Federal Emergency Management Agency

March 29, 2002
(Date)

Arden L. Bement, Jr., Director

Arden L. Bement, Jr., was sworn in as the 12th director of NIST on Dec. 7, 2001. Bement oversees an agency with an annual budget of about $812 million and an onsite research and administrative staff of about 3,000, complemented by a NIST-sponsored network of 2,000 locally managed manufacturing and business specialists serving smaller manufacturers across the United States. Prior to his appointment as NIST director, Bement served as the David A. Ross Distinguished Professor of Nuclear Engineering and head of the School of Nuclear Engineering at Purdue University. He has held appointments at Purdue University in the schools of NuclearEngineering, Materials Engineering, and Electrical and ComputerEngineering, as well as a courtesy appointment in the KrannertSchool of Management. He was director of the MidwestSuperconductivity Consortium and the Consortium for the IntelligentManagement of the Electrical Power Grid.

Bement came to his position as NIST director well versed in the workings of the agency, having previously served as head of the Visiting Committee on Advanced Technology, the agency's primary private-sector policy adviser; as head of the advisory committee for NIST's Advanced Technology Program; and on the Board of Overseers for the Malcolm Baldrige National Quality Award.

Bement joined the Purdue faculty in 1992 after a 39-year career in industry, government, and academia. These positions included: vice president of technical resources and of science and technology for TRW Inc. (1980-1992); deputy under secretary of defense for research and engineering (1979-1980); director, Office of Materials Science, DARPA (1976-1979); professor of nuclear materials, MIT (1970-1976); manager, Fuels and Materials Department and the Metallurgy Research Department, Battelle Northwest Laboratories (1965-1970); and senior research associate, General Electric Co. (1954-1965).

Along with his NIST advisory roles, Bement served as a member of the U.S. National Science Board, the governing board for the National Science Foundation, from 1989 to 1995. He also chaired the Commission for Engineering and Technical Studies and the National Materials Advisory Board of the National Research Council; was a member of the Space Station Utilization Advisory Subcommittee and the Commercialization and Technology Advisory Committee for NASA; and consulted for the Department of Energy's Argonne National Laboratory and Idaho Nuclear Energy and Environmental Laboratory.

He has been a director of Keithley Instruments Inc. and the Lord Corp. and was a member of the Science and Technology Advisory Committee for the Howmet Corp. (a division of ALCOA).

Bement holds an engineer of metallurgy degree from the Colorado School of Mines, a master's degree in metallurgical engineering from the University of Idaho, a doctorate degree in metallurgical engineering from the University of Michigan, and a honorary doctorate degree in engineering from Cleveland State University. He is a member of the U.S. National Academy of Engineering.

Chairman BOEHLERT. Thank you very much, Dr. Bement.

Here is the situation on the Floor. We have 12½ minutes remaining with this vote. So, Professor Corbett, we will go with you and—five, six minutes or so, seven, if you need, and then we will take a brief recess and dash over and vote and come back here. Okay.

STATEMENT OF PROFESSOR GLENN P. CORBETT, ASSISTANT PROFESSOR OF FIRE SCIENCES, JOHN JAY COLLEGE OF CRIMINAL JUSTICE, NEW YORK CITY

Mr. CORBETT. Thank you. Good afternoon, Chairman Boehlert, Ranking Member Hall, and Members of the House Science Committee. Thank you for allowing me to again testify before you about the investigation of the World Trade Center disaster.

Nearly 8 months have passed since the collapse of the Twin Towers, yet today we are only beginning to understand exactly what happened on September 11 at the World Trade Center. While the Building Performance Assessment Team report, that is being released at today's hearing, yields some useful information, the generalized nature of its recommendations and the limited scope of its assessment leave us with little hard evidence for which to make specific improvements to the codes, design practices, emergency response procedures. The recommendations in this report provide us with a useful starting point, but much, much work needs to be conducted.

The proposed NIST investigation that is under consideration today is the type of large-scale forensic inquiry that the Federal Government should have launched back in September. I was pleased to learn that NIST plans to conduct a thorough and comprehensive investigation incorporating the six focus areas that I identified in my testimony before this Committee on March 6. They intend to take a multi-disciplinary approach, allowing for the investigation to benefit from the expertise of a wide range of experts and to permit the disaster to be studied holistically. The breadth and depth of this planned investigation will provide as complete an understanding of the disaster at the World Trade Center as is now possible.

The fact-finding leave-no-stone-unturned objective of the NIST investigation will allow us to develop detailed conclusions and learn the lessons about what transpired at the Trade Center. It is this application of these hard-earned lessons, of course, that is the primary reason for conducting the investigation in the first place. These lessons must be translated into actual changes to our building and fire codes, enhancements in building design methodologies, and improvements in emergency response procedures and technologies.

While NIST has laid out a comprehensive proposal for investigating and researching the lessons learned from the disaster, the key to achieving this goal lies in the details of the NIST plan. This is where I will focus my comments today.

I have reviewed several draft documents concerning the actual plan for the NIST investigation. I have identified three particular areas of concern. One, the need for a rapid assemblage of a diverse group of individuals to form the core Federal Advisory Committee which will oversee the investigation; two, the need for subpoena power for the investigation, and, number three, the need for the investigation to be centered upon the development of defensible and detailed proposals for changes in building and fire codes, as well as improvements in emergency response procedures and technologies. While I am aware that NIST is attempting to deal with these three issues, I think that it is very important to highlight these concerns in light of what happened in the preparation of the BPAT report.

The Federal Advisory Committee's critical role will be the review of the NIST draft plan for the investigation and its ongoing role of monitoring the investigation. These duties are very important in light of the multidisciplinary aspects of the investigation and since some areas of the investigation involve issues that are outside of NIST's traditional areas of expertise, such as building evacuation, fire fighting, and urban search and rescue.

It is essential that the committee be composed of many individuals with a broad range of expertise and experience. It is equally important that the committee be formed as quickly as possible to allow for the rapid development and implementation of the best plan possible.

A review of NIST's current draft plan has spotlighted the need for guidance of the world-class experts of the Federal Advisory Committee. For example, the evacuation portion of the draft plan does not propose that individual interviews of survivors be conducted, but rather relies on the use of survey forms to collect information. A one-size-fits-all survey form will not gather all of the critical information that is necessary to understand the evacuations that took place on September 11th. In order to gain all the valuable data, including unanticipated information, actual interviews of the survivors must be conducted.

In addition, the interview process itself will allow for the presence of a mental healthcare professional who can help the survivor address the emotions that will be unleashed when asking questions about how they survived. Federal Advisory Committee members with expertise in human behavior and building evacuations would be able to provide such useful information, such as the development of such an interview plan, as well as the anticipated costs.

The need for diversity of expertise became evident in my review of the BPAT report. For example, the BPAT report recommends the development of training materials and courses for emergency response personnel with regards to effects of fire on steel. In reality, there are several books and training materials currently available concerning building construction, including large portions of information on steel frame buildings and the effects of fire on steel.

FEMA itself, through the U.S. Fire Administration, publishes a very popular training program called the Principles of Building

Construction: Noncombustible. I believe that had a firefighter been on the BPAT team, this fact would have been quickly identified.

The second area of concern is the need for subpoena power. In order to thoroughly investigate the Trade Center disaster, investigators must have access to all relevant information. It is only with a full set of facts that conclusions may be drawn. My—the experience in the preparation of the BPAT study has identified this as a key issue. The Science Committee hearing on March 6 clearly highlighted some of the impediments the BPAT faced in obtaining key information. My fear is that the NIST investigation will be hindered by these same problems.

Information may be found in a variety of locations and may be held by different individuals and organizations that will not provide this information voluntarily. Even though the WTC investigation is an investigation of a fact-finding nature, a legal means for obtaining information that would otherwise be unavailable must be provided for investigators.

The third area of concern is to learn as many lessons as possible and to apply these lessons. In order for the changes to building and fire codes to be applied, the NIST investigation and the research reports must include specific recommended changes to specific sections of our model codes, not generalized recommendations.

For example, in the Observations, Findings, and Recommendations chapter of the BPAT study, the report states that, "Fireproofing needs to be tough under impact and fire conditions that deform steel members." This conclusion will not easily find its way into the model codes since it is not in proper code format and lacks the corresponding necessary supporting evidence. NIST must recognize this fact if the ultimate goal is to actually improve building codes, standards, and practices.

These proposed changes and related supporting evidence developed by NIST must be laid at the feet of the code-writing organizations for inclusion in their model codes. In addition, I believe that a special, formalized code change submittal process must be developed between NIST and the code-writing bodies to address the code changes that will emerge from this investigation. This more formalized relationship will raise many difficult questions, which are likely outside the scope of this hearing. However, the Science Committee should continue to look at this issue and see what barriers must be overcome.

I believe that the proposed NIST investigation is the best course of action to learn and apply the lessons of the Trade Center disaster. It is critical that the investigation be as comprehensive as currently planned and be funded at the necessary level to achieve this goal. It is essential that we learn exactly what happened to these structures, victims, and survivors on September 11 and try to prevent it from ever happening again.

Thank you for allowing me to testify before you on this very important topic. I would be happy to answer any questions that you may have.

[The prepared statement of Mr. Corbett follows:]

PREPARED STATEMENT OF GLENN P. CORBETT

Good afternoon Chairman Boehlert, Ranking Member Hall, and Members of the House Science Committee. Thank you for allowing me to again testify before you about the investigation of the World Trade Center disaster.

Nearly eight months have passed since the collapse of the twin towers, yet today we are only just beginning to understand exactly what happened on September 11th at the World Trade Center (WTC). While the Building Performance Assessment Team (BPAT) report that is being released at today's hearing yields some useful information, the generalized nature of its recommendations and the limited scope of the assessment leave us with little hard evidence for which to make specific improvements to codes, design practices, and emergency response procedures. The recommendations of this report provide us with a useful starting point, but much work remains to be done.

The proposed National Institute of Standards and Technology (NIST) investigation that is under consideration today is the type of large-scale forensic inquiry that the federal government should have launched last September. I was pleased to learn that NIST plans to conduct a thorough and comprehensive investigation, incorporating the six focus areas that I identified in my testimony before this Committee on March 6th. They intend to take a multi-disciplinary approach, allowing for the investigation to benefit from the expertise of a wide range of experts and to permit the disaster to be studied holistically. The depth and breadth of the planned investigation will provide as complete an understanding of the disaster at the World Trade Center as is now possible.

The fact-finding "leave no stone unturned" objective of the NIST investigation will allow us to develop detailed conclusions and learn the lessons about what transpired at the World Trade Center. It is the application of these hard-earned lessons, of course, that is the primary reason for conducting the investigation in the first place. These lessons must be translated into actual changes to our building and fire codes, enhancements in building design methodologies, and improvements in emergency response procedures and technologies. While NIST has laid out a comprehensive proposal for investigating and researching the lessons learned from the disaster, the key to achieving this goal lies in the details of the NIST plan. This is where I will focus my comments today.

After having reviewed several draft documents concerning the actual plan for the NIST investigation, I have identified three particular areas of concern: 1) the need for the *rapid* assemblage of a diverse group of individuals to form the core "Federal Advisory Committee" which will oversee the investigation; 2) the need for subpoena power for the investigation; and 3) the need for the investigation to be centered upon the development of "defensible" and detailed proposals for changes in building and fire codes as well as improvements in emergency response procedures and technologies. While I am aware that NIST is attempting to deal with these three issues, I think that it is important to highlight these concerns in light of what has happened in the preparation of the BPAT report.

The Federal Advisory Committee's critical role will be its review of NIST's draft plan for the investigation and in its ongoing role of monitoring the investigation. These duties are very important in light of the multidisciplinary aspects of the investigation and since some areas of the investigation involve issues that are outside of NIST's traditional areas of expertise such as building evacuation, firefighting, and urban search and rescue. It is essential that the Committee is composed of many individuals with a broad range of expertise and experience. It is equally important that the Committee be formed as quickly as possible to allow for the rapid development and implementation of the best plan possible.

A review of NIST's current draft plan has spotlighted the need for the guidance of the "world class experts" of the Federal Advisory Committee. For example, the "evacuation" portion of the draft plan does not propose that individual interviews of survivors be conducted but rather relies on the use of survey forms to collect information. A "one size fits all" survey form will not gather all of the critical information that is necessary to understand the evacuations that took place on September 11th. In order to gain all valuable data including unanticipated information, actual interviews of the survivors must be conducted. In addition, the interview process itself will allow for the presence of a mental health care professional who can help the survivor address the emotions that will be unleashed when asking questions about how they survived. Federal Advisory Committee members with expertise in human behavior and building evacuations would be able to provide useful information for the development of such an interview plan as well as the anticipated costs.

This need for diversity of expertise became evident in my review of the BPAT report. For example, the BPAT report recommends the development of ". . .training materials and courses for emergency personnel with regards to effects of fire on steel." In reality, there are several books and training materials currently available concerning building construction, including large amounts of information on steel frame buildings and the effects of fire on steel. Ironically, FEMA itself (through the United States Fire Administration) publishes a very popular training program called "Principles of Building Construction: Noncombustible." I believe that had a firefighter been on the BPAT team, this fact would have been quickly identified.

The second area of concern is the need for subpoena power. In order to thoroughly investigate the WTC disaster, investigators must have access to all relevant information. It is only with a full set of facts that conclusions may be drawn. The experience in the preparation of the BPAT study has identified this as a key issue. The Science Committee hearing on March 6th clearly highlighted some of the impediments the BPAT faced in obtaining key information. My fear is that the NIST investigation will be hindered by these same problems.

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For example, in the Observations, Findings, and Recommendations chapter of the BPAT study, the report states "Fireproofing needs to be tough under impact and fire conditions that deform steel members, . . ." This conclusion will not easily find its way into the model codes since it is not in the proper code format and lacks the corresponding necessary supporting evidence. NIST must recognize this fact if the ultimate goal is to actually improve building codes, standards, and practices.

These proposed changes and related supporting evidence developed by NIST must be laid at the feet of the code-writing organizations for inclusion in their model codes. In addition, I believe that a special, formalized code change submittal process should be developed between NIST and the code-writing bodies to address the code changes that will emerge from this investigation. This more formalized relationship will raise many difficult questions, which are likely outside the scope of this hearing. However, the Science Committee should continue to look into this issue to see what barriers must be overcome.

I believe that the proposed NIST investigation is the best course of action to learn and apply the lessons of the World Trade Center disaster. It is critical that the investigation be as comprehensive as currently planned and be funded at the necessary level to achieve this goal. It is essential that we learn exactly what happened to the structures, victims, and survivors on September 11th and try to prevent it from ever happening again.

Thank you for allowing me to appear before you on this very important topic. I would be happy to answer any questions that you may have.

GLENN P. CORBETT

136 Bergen Avenue
Waldwick, New Jersey 07463

Home:(201) 652- 9224
Work: (212) 237- 8092

SUMMARY: Extensive experience in different facets of fire protection including the fields of firefighting and fire prevention. In-depth knowledge of the development and trends of the American fire protection profession.

EXPERIENCE:

January 1995 to Present **John Jay College of Criminal Justice**, New York, New York
Assistant Professor of Fire Science
Coordinator, Undergraduate Fire Science Programs
Director, Graduate Protection Management Program (Jan. 1995 – June 1997)

- Prepare and teach fire science courses at the undergraduate and graduate level
- Manage and coordinate course offerings in undergraduate fire science and fire and emergency services programs, including internet offerings
- Provide guidance to existing and prospective fire science students

Sept. 1994 to Dec. 1994 Lecturer, Fire Science

April 1993 to April 1994 **PennWell Publishing Company**, Saddle Brook, New Jersey
Technical Director, *Industrial Fire Safety* Magazine

- Provided and maintained technical editorial direction of an industrial fire protection and safety magazine, *Industrial Fire Safety*
- Reviewed all articles submitted for publication for accuracy and relevancy

August 1987 to April 1993 **San Antonio Fire Department**, San Antonio, Texas
Administrator of Engineering Services

- Established Engineering Services Office, including procedures, policies, and the physical plant
- Directed and evaluated staff consisting of fire protection engineer and 3 plan reviewers
- Managed all plan reviews conducted by the department including (annually) 2000 building permits (1500 interior remodels, 500 new structures) and fire protection system plans (500 sprinkler, 350 fire alarm, and other types of systems)
- Coordinated fire prevention activities with other city departments such as Building Inspections and Planning
- Coordinated, prepared, and taught 250+ hour fire inspector training course
- Served/assisted various city committees such as a Development Task Force, Board of Appeals, and Blue Ribbon Fire Department Study
- Provided technical assistance to architects, engineers, developers, and contractors
- Assisted in the preparation of new fire code and amendments

March 1986 to August 1987 **Austin Fire Department**, Austin, Texas
Fire Protection Engineer

- Reviewed fire protection system plans as well as water supply plans for code compliance
- Assisted uniformed personnel in the review of building permit plans
- Assisted in the preparation of code policy manual for development community
- Responded to multiple alarm fires to provide on-scene technical assistance

1985 **A.B.C. Loss and Fire Prevention Corp.**, East Orange New Jersey
Loss Prevention Consultant

- Estimated and designed automatic sprinkler systems

- Monitored sprinkler system installations and evaluated existing systems

Concurrent *Fire Engineering* Magazine, **PennWell Publishing Company**, Fair Lawn, N.J.
Consulting Editor, August 1986 - September 1990
Editorial Advisory Board Member/Columnist, October 1990 - April 1993
Technical Editor/Columnist, April 1993 - Present
Fire Department Instructors Conference Planning Committee member (1997 - present)

1978 - 1986 & 1994 - present **Waldwick Volunteer Fire Department,** Waldwick, New Jersey
Volunteer Firefighter (Through Dec. 1995)
Deputy Municipal Fire Coordinator (Jan. 1996 – Aug. 1997)
Second Lieutenant (Sept. 1997 – Dec. 1997)
First Lieutenant (Jan. 1998- Dec. 1998)
Second Captain (Jan. 1999 – Dec. 2001)
First Captain (Jan. 2002 – Present)

1979 - 1986 **Paterson Fire Department,** Paterson, New Jersey
Auxiliary Firefighter

EDUCATION: Worcester Polytechnic Institute, Worcester Massachusetts
1991 M. Eng., Fire Protection Engineering
Thesis: "Water Supply Evaluation for Firefighting"

John Jay College of Criminal Justice, New York, New York
1982 B.A., Fire Service Administration, Cum Laude
Dean's List, 1979 - 1982

MEMBER: Bergen County Fire Chief's Association
International Association of Fire Chiefs
International Society of Fire Service Instructors
National Fire Protection Association
New Jersey Society of Fire Service Instructors (currently serving as President)
Society of Fire Protection Engineers

COMMITTEE: "America Burning: Re-commissioned" Panel, appointed By Federal Emergency Management Agency (FEMA) Director James Lee Witt in August 1999

Fire Code Advisory Council, State of New Jersey

CERTIFICATION/LICENSE:
State of Texas:
Professional Engineer's License, # 80114
Inactive certification as Class "A" Fire Inspector and Basic Fire Instructor

State of New Jersey:
Firefighter I, # 109356
Fire Official, # A007103

May 1, 2002

The Honorable Sherwood Boehlert
Chairman, House Science Committee
2320 Rayburn House Office Building
Washington, DC 20515

Dear Congressman Boehlert:

Thank you for the invitation to testify before the U.S. House of Representatives Committee on Science, on May 1, 2002 for the hearing entitled, "The Investigation of the World Trade Center Collapse: Findings, Recommendations and Next Steps." In accordance with the Rules Governing Testimony, this letter serves as formal notice that I currently receive no federal funding in support of my research.

Thank you again for the opportunity to speak about this important issue.

Sincerely ,

Prof. Glenn P. Corbett
John Jay College of Criminal Justice/CUNY

Chairman BOEHLERT. Thank you very much, Professor. And thank you for a very fine presentation. We have 4 minutes and 40 seconds to vote. I would anticipate a break of about 20 minutes. We are going to dash over and then there is this vote and then a vote on passage of the bill in question. We will do it and get right back over as soon as we can. So you have got about 20 minutes to sort of catch your breath and then we will come back for the question period.

[Recess]

DISCUSSION

Chairman BOEHLERT. Let us resume. Colleagues will be wandering back from the Floor, but let us get started. Thank you all for your statements; I appreciate it. Let us get right to the questions. First, Dr. Bement, you have some resources, based upon existing allocations, that enable you to start right away.

Dr. BEMENT. That is correct.

Chairman BOEHLERT. You don't even have to delay anything.

Dr. BEMENT. And we aren't.

Chairman BOEHLERT. And you are not waiting for a supplemental, although we understand the President is going to request $16 million in the supplemental and you need that. But you have got something to start.

Dr. BEMENT. That is correct.

Chairman BOEHLERT. No excuse for any delays at all.

Dr. BEMENT. That is correct.

EVACUATION/EMERGENCY RESPONSE PROCEDURES

Chairman BOEHLERT. Thank you. All right. Now, I will ask this of all witnesses, because I think this gets right to the heart of something very important, my sense is that changes in evacuation procedures and emergency response procedures may be, by far, the most important results of this tragedy. I would like to know if you agree with that. Let me go right down the Panel. Mr. Shea.

Mr. SHEA. Yes, Mr. Chairman. I do agree with that. Actually, when we spoke before on March 6, those were some of the areas of my highest concern about what had taken place, and I think the work that Dr. Corley and his team has done have kind of proven that concern out at this point.

Chairman BOEHLERT. Dr. Corley.

Dr. CORLEY. Yes. I think that is a very important consideration. I would point out, in fact, that at the Trade Center, since they had been attacked once before, they had already instituted very good training programs and they practiced evacuating the building. And we believe that that was one of the things that reduced the number of casualties. People knew what to do, and when they were faced with the need to do it, they did it. So that was important and it needs to be further emphasized in any building in the future.

Chairman BOEHLERT. All right. Dr. Bement.

Dr. BEMENT. Absolutely. Let me emphasize that we are not doing just surveys. We are doing actual interviews and we will capture oral history on survivors and also first responders that were involved in the World Trade Center collapse.

Chairman BOEHLERT. I am glad you made that point because surveys by themselves would not be sufficient.

Dr. BEMENT. Absolutely.

Chairman BOEHLERT. And you would agree with that?

Dr. BEMENT. Absolutely.

Chairman BOEHLERT. All right. Fine. Professor Corbett.

Mr. CORBETT. Yes.

Chairman BOEHLERT. And you may be the only person on this panel that can pass the objectivity test, in a sense. I don't say that with any prejudice, but you are an independent operator and you are noted for saying exactly what is on your mind.

Mr. CORBETT. Thank you. Yes.

Chairman BOEHLERT. Thank you.

Mr. CORBETT. Well, most definitely. And that is the reason why I identified this back on March 6 as two focus areas—the evacuation and emergency response procedures. We have never had this done before on such a large scale. I am glad to hear Dr. Bement mention that they will be doing a large number—or I should—I didn't want to say a large number, because they are planning on doing interviews—but I would suggest that they need to do a large scale amount of interviews, very many of them basically.

Chairman BOEHLERT. Right.

Dr. BEMENT. One other point. I don't share Dr. Corley's conclusions about the egress in those buildings. I mean, we all know that there were people that believed that they could have gone to the roof to get off. And I don't know, without, again, going much more deeply into the actual procedures that were in place at the Trade Center, to find out, in fact, if people were ever told, for example, that they could get to the roof for evacuation. It seems that—again, just from what I have heard—that the people that survived above the points of impact made a conscious decision not to go to the roof and, in fact, went down instead of up. So I think that is a very, very important issue to look at.

ACCESS TO INVESTIGATION MATERIALS

Chairman BOEHLERT. Yeah. Which leads me, Dr. Corley, to ask what kinds of materials your team was never able to review that would have helped the investigation? We understand, for example, that you were never able to gain access to the 911 tapes and some news media videotapes that were never broadcast.

Dr. CORLEY. I will pass that question to my colleague here.

Chairman BOEHLERT. Dr. Barnett.

Dr. BARNETT. Thank you. The week before we went to the site I was the one who requested the 911 tapes and transcripts. But our use for that information was to understand how the fire was growing and spreading through the building. That was, at that time, what we anticipated as the most important use of the information.

In December, or early January, I withdrew my request because by then we realized that the computer modeling that we would have used the 911 transcripts to validate was not going to be completed in time for the BPAT report. And, in fact, that modeling is still underway and will be underway at NIST. It is certainly underway in my office.

Chairman BOEHLERT. Well, how about the news media and the videotapes? I want to ask all of you to comment on the bill that I am going to introduce. Mr. Weiner and I have worked very hard on this thing and we are going to introduce it. But, would you agree that somebody should have had immediate subpoena power to get that information. Dr. Corley, don't you think that would have helped immeasurably in your investigation?

Dr. CORLEY. Certainly. When you start one of these studies, the faster you get the information, the more you can do with it. And, indeed, it would have helped if we could have obtained that information more quickly than——

Chairman BOEHLERT. Are they still useful, do you think?

Dr. CORLEY. Yes. Absolutely.

Chairman BOEHLERT. Do they still exist?

Dr. CORLEY. They still exist and they still would be useful.

Chairman BOEHLERT. Should NIST have them, Dr. Bement?

Dr. BEMENT. We have discussed this matter with the National Transportation Safety Board and they advise that having the power, even though you don't have to use it, can be important. So we have been examining this issue very carefully and examining the pros and cons, and it is under active consideration.

Chairman BOEHLERT. Are you going to go after the tapes?

Dr. BEMENT. We are going to go after every piece of evidence that bears on this——

Chairman BOEHLERT. And the media has videotapes?

Dr. BEMENT. Absolutely.

Chairman BOEHLERT. All right. So you are definitely going after that. That is good news.

Dr. BEMENT. That is correct.

Chairman BOEHLERT. My red light is on, and I want to be fair to everybody on this Panel, but we are going to have maybe several rounds. So with that, the Chair recognizes Mr. Weiner.

STAIRWELL SEPARATION

Mr. WEINER. Thank you, Mr. Chairman. I would like to try to walk you past what are recommendations and findings and try to reach a few conclusions if I could. In your presentation, Dr. Corley, you said that there needs to be, in future buildings, sufficient separation of stairwells. Given that, in Building 1, three of three stairwells were knocked out; in Building 2, at least two of three, and maybe all three, at some point, got knocked out. Would you say there was insufficient separation of the stairwells in the World Trade Centers as they were built?

Dr. CORLEY. As the buildings were built, no, I would not say it was insufficient, because they were built not recognizing that terrorists might attack the buildings as they did.

Mr. WEINER. Dr. Corley, that is intuitive. It is intuitive that no one modeled for this. But I am asking you a different question. Now that you have gone in and looked after the fact, it is a conclusion that you can draw, at this point, that for the purposes of getting people out of those buildings, the stairwells were not sufficiently separated?

Dr. CORLEY. Our conclusion is that if they had been further separated, there would have been a better possibility of getting them out of the building.

Mr. WEINER. Okay. In your testimony, you said that it was important to have a redundancy of water supply for the sprinklers. Is it fair to say that since the sprinkler system was knocked out almost at impact, it is thought, that there was not sufficient redundancy of the sprinkler system?

Dr. CORLEY. In this case, once the supply for the water was knocked out, there was not a sufficient amount of water left in the system to be of any value.

Mr. WEINER. Dr. Corley, given what you say, or your findings, was there sufficient redundancy of the sprinkler system in the World Trade Center on September 11?

Dr. CORLEY. For the case where an airplane hits the building, as it did here——

Mr. WEINER. Not for a case. For the case of what happened on the morning of September 11. For that case.

Dr. CORLEY. For that case, when the airplane hit the building and did this tremendous amount of damage, there was no adequate redundancy of——

SPRINKLER SYSTEM REDUNDANCY

Mr. WEINER. There was not sufficient redundancy. So we have already established there was not sufficient separation of the stairwells and there was not sufficient redundancy of the sprinkler system. You also—yes, sir.

Dr. CORLEY. Could I just add one comment?

Mr. WEINER. Certainly.

Dr. CORLEY. Dr. Barnett would like to add a comment to that.

Dr. BARNETT. In addition to the water supply, we do not design sprinkler systems for multiple floors, entire floors of buildings, to be involved in fire simultaneously. We design our sprinkler systems for a small fire that grows. All right. So even with a redundant water supply, the sprinkler system would not have worked, would not have been able to control the fires. We just don't design that way.

Mr. WEINER. Dr. Corley, in your testimony, you said one of the lessons we learned is there needs to be sufficient redundancy of the sprinkler system. Was there sufficient redundancy of the sprinkler system in the World Trade Center?

Dr. CORLEY. There was not for the conditions——

Mr. WEINER. Okay.

Dr. CORLEY [continuing]. That occurred.

EGRESS SYSTEMS

Mr. WEINER. Obviously. In addition, in your testimony, you say it is important to have robust egress systems, reinforcements of the areas where people are going to be coming and going from. Given what we know and given your report, can you draw the conclusion that there were not sufficiently robust egress systems?

Dr. CORLEY. Again, for the condition with the aircraft that hit this building, they knocked the walls out. We have eyewitness accounts of that. And it was not—they were not capable of resisting this impact.

Mr. WEINER. Okay. Can I ask you—one of the things, that is—and those are three conclusions that, while you don't call them conclusions, I think it is reasonable now to say those are conclusions that can be drawn. I was impressed, among other things, with how many times within the report it is said, in one language or another, we didn't look at this and we probably ought to. We didn't look at that and we probably ought to. Does this report speak at all about elevator design, reinforcing the infrastructure around elevators to allow them to be used? In some cases they failed, in other cases they were in use. Is there any discussion about design issues surrounding elevators?

Dr. CORLEY. No, sir. We did not address that.

Mr. WEINER. Is there any discussion in this document or any analysis done to pick up on what the Chairman mentioned, on allowing for egress from the roof or allowing an emergency helicopter to land on the roof of a building—any design questions that occurred in that context?

Dr. CORLEY. No, sir. There is none.

BUILDING CODES

Mr. WEINER. Okay. Let me just ask you finally about the issue of building codes. One of the things that I think we would all hope that would come out of any investigation would be a discussion about lessons they can learn and how they can be transferred to other things. I am reading from Chapter 8, Subsection 3. Actually, I see the red light is on. Let me just summarize. Was there anything in this report that a city council, that a state legislature, or that the Federal Government can take and translate directly into changes in building codes?

Dr. CORLEY. Not at this time. There are several things that we anticipate will be ready to go in the future, but at the moment we don't have the wording that we would use. We don't know what the parameters are that should be suggested, but we can see some things that may be changes in the future.

Mr. WEINER. Thank you, Mr. Chairman.

Chairman BOEHLERT. Thank you. Thanks, Mr. Weiner. And you can understand the passion that is up here. But that is exactly, Mr. Weiner, why we have to have the follow-through from this in a very comprehensive way. And that is why we are so anxious to determine if they have the resources to begin immediately and not have to wait for some supplemental request, etcetera, etcetera. And obviously, Dr. Corley, and the team, the study was not complete. We all recognize that right from the beginning. I mean, we wish we had more time, more resources, more of everything. But we are moving in the correct direction, and that is critically important. The Chair recognizes Dr. Ehlers.

WTC BUILDING 7

Mr. EHLERS. Thank you, Mr. Chairman, and thank you for holding this very important hearing. I understand fully why Towers 1 and 2 went down based on the description you have given. I am still puzzled by Building #7, World Trade Center #7, which you said collapsed because of a lengthy fire. Were the sprinklers destroyed in that building? Did the insulation come off of the steel there as well? What actually happened in that building?

Dr. CORLEY. Building #7 is, indeed, one of the more important buildings that we looked at, and we do have answers to some of your questions, which are addressed in the report. We were not able to find any evidence that the sprinklers worked in the building. We believe it is mainly because there was damage to the water supply system, and the water pressure that was available just wasn't sufficient to supply water to the sprinklers in the building.

Mr. EHLERS. Where was the damage to the water system?

Dr. CORLEY. The water system was damaged in several locations. The falling debris penetrated the ground and actually took out parts of the water supply for the World Trade Center area. It took several hours after the collapses of 1 and 2 before the city could first find out where those were and then isolate those leaks so they could, again, supply a reasonable amount of water to that area. In the meantime, the fire department, we were told, was forced to take water out of the river to help them to fight the fires that occurred after the collapses.

As far as the fireproofing for Building 7, we have no evidence that it was knocked off as a result of damage from debris coming from either of the two towers. There was evidence the building was struck by some of the debris. We have been unable to quantify how much damage there was. We did not conclude that the fireproofing was knocked out. We believe it was a fire that continued to burn for a long period of time, meaning it had a very large source of fuel. And other than that, it was a building that came down just from the fire and without substantial structural damage.

Mr. EHLERS. That is a real concern to me. Because are the beams and girders designed to withstand the fire with the insulation in place?

Dr. CORLEY. I will ask Professor Barnett to address that part of it.

Dr. BARNETT. Thank you. The building codes specify performance in a standard fire-resistance test. The building codes do not specify performance in real fires. So the buildings are designed in accordance with the standard and the tests. Our history has been excellent. Up until 9/11, we had never had a collapse of a protected steel building. But we have now had one. We now need to look and see what occurred. This is a problem. You are right. And this is of great concern to all of us.

Mr. EHLERS. So I presume that you should have better tests or better standards so that you thoroughly understand that. And, Dr. Bement, I assume that would be part of your ongoing work.

Dr. BEMENT. Yes, sir. Well, we already have predictive codes, that go beyond the ASDN code method E–119, which is being referred to. And we certainly would want to use that in a way that would predict fire behavior for a type of fire such as this one, and would give more than an indication of how the structures would survive or how they would perform under those specific conditions.

Mr. EHLERS. And, Dr. Bement, continuing with you, it strikes me that investigating 7 might be the most interesting aspect. And do you plan to devote a fair amount of your time——

Dr. BEMENT. Yes.

Mr. EHLERS [continuing]. And dollars to that effort?

Dr. BEMENT. It would certainly be a main part of our investigation. There are still some unanswered questions about that building. It did house a Con-Ed generating substation. There were pipes that provided fuel to emergency generators. And there is still an open question in the report about whether or not the fire loading, the fuel that loaded the fire, might have been contributed to by a broken pipe that may have provided diesel fuel. I think we need to model that fire and determine whether or not that was a factor.

STAIRWELL MATERIALS

Mr. EHLERS. One last quick question, Dr. Corley. And that is, if the stair walls in 1 and 2 had been concrete, would that have been able to withstand the impact?

Dr. CORLEY. The answer to that question cannot be answered strictly on the basis of what material was used. It is the way in which the materials are used that is important. So for any of the materials that are commonly used to enclose stairs, you would have to do an analysis of it, see how it is attached to the frame of the building, see what its resistance is to the impact and debris that was created by the planes crashing into the building, and you would have to answer that on the basis of how it was designed.

So it is not possible to just say if it was a different material, it would have worked, and with the materials used, it wouldn't work. You would have to do an engineering analysis.

Mr. EHLERS. And are you sure the insulation came off from the impact?

Dr. CORLEY. We have very good evidence that it did. We have photographic evidence that shows steel that we have interpreted to be steel that no longer has fireproofing on it. In addition to that, though, we have the other buildings that did not burn where they were impacted by debris coming from the towers, and we found that the fireproofing was knocked off of the steel in the areas where the debris hit there. So that is additional evidence that drew us to our conclusion that it was knocked off in the towers.

NIST SUBPOENA POWER

Chairman BOEHLERT. Thank you. And the gentleman's time has expired. There will be opportunity for another round of questioning. Dr. Bement, I want to just follow through for one moment before going to Mr. Shays on the subpoena power. As you know, our draft legislation, my bill, has——

Dr. BEMENT. Yes.

Chairman BOEHLERT [continuing]. Subpoena power in there.

Dr. BEMENT. Yes.

Chairman BOEHLERT. But there have been officials within NIST that have suggested that that is very important. Have you made that formal request within the Administration, and what is the status of that request?

Dr. BEMENT. It is under active discussion at the present time.

Chairman BOEHLERT. And how active and how long?

Dr. BEMENT. Hopefully not long and quite active.

Chairman BOEHLERT. Well, that is the answer I want to hear. But, at what level?

Dr. BEMENT. It is higher than my level at this point.

Chairman BOEHLERT. Well, I mean, to me it is a no-brainer. You absolutely need it. And we are going to give it to you in short order, I think, probably within a matter of weeks—well, within a matter of weeks, rather than months. But I would like to think that the Administration would give it the priority attention it deserves so you can get it right away. Does it make much sense to start the investigation without that?

Dr. BEMENT. I live in hope.

Chairman BOEHLERT. Okay. You are a diplomat. The Chair recognizes Mr. Shays.

STAIRWELL SEPARATION/WATER SYSTEM REDUNDANCY

Mr. SHAYS. Thank you, Mr. Chairman, for holding these hearings. I am sorry I missed the beginning. I was chairing my own committee, the National Security Subcommittee. Gentlemen, what you all are doing is very, very important.

And I found myself thinking that I am still one of those skeptics believing that it would have been impossible to prevent these buildings from collapsing given what attacked them, a gigantic plane with a tremendous amount of fuel, one plane traveling at close to 500 miles an hour. So when I hear a question about the redundancy of the water supply, I think, my God, it knocked out a few floors. You could have had ten redundancies and they all would have been wiped out in that instance.

But having said that, you all have learned things, it seems to me, that will be very helpful in what we do in the future, and some good lessons and some bad lessons. Can I make an assumption, from Mr. Weiner's question, that if we were to have the stairwells separated more, that that would be a positive thing in the future in any building?

Dr. CORLEY. Yes. In our opinion, that would be a positive thing to do. Then if there was an impact to the building, you would have a statistically better chance that the stairs would be available.

Mr. SHAYS. I mean, in a way, did we almost design this building like the Titanic, in that we didn't have enough life boats? I mean, is it even conceivable that you can get out of a building in time with the number of stairways that we had?

Dr. CORLEY. If I may address that. There is always the possibility of yet a larger aircraft hitting whatever building you design. So we concluded in our report that it is possible that you may not be able to design a building to resist anything that might happen in the future.

What we do address, though, is that if you take advantage of what we are learning here, and that is that the stairwells appear that they would have done better if they were spread out more, then in the future, if another building is hit like this one was, at least you would increase the odds. We don't believe that you can guarantee, though, that it will resist all of the——

Mr. SHAYS. Right.

Dr. CORLEY [continuing]. Things that are possible.

Mr. SHAYS. And, yet, it was a minor miracle that given all the people in this building, most were able to get out, certainly below. I mean, a minor miracle—a major miracle. And I am told by one of my friends, a high school friend who was in this building, but was there in the first bombing when five floors were basically knocked out, as soon as the first tower was hit, he told his staff to leave the building. And he said that they had practiced, in a sense, what to do. They knew what to do. And he said, if the first bombing hadn't taken place, a lot more people would have lost their lives. Some would have stayed in the building and some wouldn't have known when to leave.

So with regards to, though, the redundancy of the water supply, notwithstanding that I could say three floors went out, so there is nothing that could prevent it. In the future for something not as catastrophic, would a redundancy in the water supply be helpful?

Dr. CORLEY. Yes. That was what our report concluded, and I will allow Jonathan to add a little bit to that.

Dr. BARNETT. Thank you, Gene. The current standards for a sprinkler design are intended to address normal fires, normal situations, and they work. When sprinklers operate, when they are designed properly, they save lives. In fact, other than people intimately involved with——

Mr. SHAYS. Yeah. I know they save lives and it is not a problem.

Dr. BARNETT. All right. Well——

Mr. SHAYS. But the question is, should there be a redundancy. I want to ask one more question before my time runs out here. Should there be a redundancy in the future?

Dr. BARNETT. We do—I think that for buildings subject to a potential terrorist event, you might want to include redundancies. The NFPA Standard 13 talks about redundant water supplies.

Mr. SHAYS. Let me ask this question then. In regard to stairways and the redundancy of the water supply, what needs to be done to get that to happen? Is that something NIST needs to do? Mr. Corbett, do you want to respond?

Mr. CORBETT. Yeah. Can I just comment on the redundancy issue?

Mr. SHAYS. Right. And then——

Mr. CORBETT. Very important. Something that we identified back on March 6 was that we treat ten-story buildings the same way as we treat 100-story buildings under our building codes today.

Mr. SHAYS. Okay.

Mr. CORBETT. I think we need to have a lot more redundancy when we are talking about very tall buildings. That is not just water supply. That is not just egress. And I think we need to have a much better protected building for very tall buildings. We can't rely on the firefighters to fly up in helicopters to attack these fires, and we need to have the ability for that building to stay intact and get the people out long enough for the fire service to do the job they need to do.

Mr. SHAYS. Mr. Chairman, could I just ask a follow-up just to conclude this issue?

Chairman BOEHLERT. By all means.

Mr. SHAYS. Given that the stairways maybe need to be further apart, given that you may need to have redundancy, what needs to be done to get the codes to require that to happen? Is that something NIST needs to do? What is going to make that happen?

Dr. CORLEY. If I may address that. First of all, there need to be additional data collection done and studies made of what you would gain with additional stairways, if anything. And we need to find out what to recommend.

Mr. SHAYS. Right.

Dr. CORLEY. And then it needs to go through the consensus process so the public can get their say in this also and develop the wording that would go in the codes if changes are found to be necessary.

Mr. SHAYS. Thank you. Thank you, Mr. Chairman.

BUILDING CODES

Chairman BOEHLERT. Dr. Corley, you know, some of the fire safety codes are based on studies dating back to 1926. Why can't we go ahead right now and make some recommended changes in building codes while the study is going forward? Dr. Bement, can you respond to that?

Dr. BEMENT. Well, redundancies——

Chairman BOEHLERT. Then I would like to ask Professor Corbett to respond too.

Dr. BEMENT. Redundancies come up and redundancy of active fire suppression is absolutely essential. On the other hand, one also has to look at defense in depth. And that involves compartmentalization. It involves passive insulation. It involves a disciplined limitation of flammable materials, fire loading. It involves all these things. And I think taking a simplistic approach in just talking about redundancy of water systems doesn't go far enough.

Chairman BOEHLERT. Uh-huh.

Dr. BEMENT. It has to go much further.

Chairman BOEHLERT. Yes. I would agree with that. You know, for every complex problem, there is always a simple solution, and it is usually wrong. Complex problems anywhere——

Dr. BEMENT. Well, I don't want to characterize it as being simple either.

Chairman BOEHLERT. Yeah. I understand that. But, Professor Corbett, let us hear some more from you.

Mr. CORBETT. Well——

Chairman BOEHLERT. I like your style.

Mr. CORBETT. Okay. Well, from a redundancy standpoint, again, to go back to the issue of how we treat buildings and building codes, there is very little relationship, in my opinion, between how we fight fires in buildings and how buildings are built. For example, when we talk about firefighter communication systems, our current codes require hard-wired systems in which the firefighters have to take telephone handsets up into buildings and plug them into walls in specific locations to communicate with the chief officers down in the command post.

That is not the way fire departments operate. They use radios, you know. We don't use these type of systems because they don't work. And, yet, this particular requirement has been the code for over 20 years. So I think the reason why I called for the comprehensive investigation here is because we have got to integrate the firefighters, the emergency responders, with the engineers and things. And I think NIST certainly understands that. And that is what should have been going on in September.

But as far as the redundancies go, again, we need to look at what specific things need to be changed. But this is a belt and suspenders situation here. You need to have both the belt and a suspender when you are dealing with very tall buildings. You cannot rely on one specific thing to work properly or we are going to have the problems that we had at the Trade Center.

NIST FUNDING NEEDS

Chairman BOEHLERT. And I couldn't agree more that the comprehensive nature of the study is essential, which leads me to conclude that you have some money to start now, Dr. Bement, and there is going to be a $16 million supplemental request. I hate to be accused of being a big spender, but that is not going to be enough.

Dr. BEMENT. No. It won't be enough.

Chairman BOEHLERT. Tell me what you need.

Dr. BEMENT. Well, that only takes care of one of the three elements of our response plan. And the remaining elements have to do with research and development, which will address many of the other recommendations that came out of the BPAT study. It will deal with connectors. It will deal with floor truss structures and their response to fire. It will deal with different materials that might be used for passive fire protection. It will deal with the issues that have been raised with regard to the robustness and the adherency of sprayed-on fire insulation on painted steel.

If we are going to be dealing with protection against blast—it doesn't have to be an airplane, in fact—it could be blast—we have to find better ways in which to apply some of these insulation materials so that they will be reliable and they can live up to whatever design code one is using for those kinds of——

Chairman BOEHLERT. Where does the $40 million figure come from? Is that a NIST——

Dr. BEMENT. Well, that was Dr. Corley's number, and I would defer to him to speak to that.

Chairman BOEHLERT. And, Dr. Corley, you are saying, what, 40 million over the next 3 years would be needed?

Dr. CORLEY. No, sir. That $40 million was intended for the additional analysis and study that we have identified needs to be done at this point. It did not include such things as the research on connections and things like that that need to be done to be able to make proper code changes in the future.

Chairman BOEHLERT. Okay. Well, Dr. Bement, I have got this chart, which I understand is an internal working document within NIST, that outlines the 40.4 million through fiscal year '05. And is that generally accepted within NIST, what Dr. Corley is suggesting?

Dr. BEMENT. We currently have identified, including the $16 million for the investigation, $30 million, part of which will be used for research and development. There will be additional needs to cover all the research and development that we have currently scoped, and those requests will come through in our '04 budget request and the outyear budget request as well.

Chairman BOEHLERT. But are you operating under the assumption that you are probably going to get those? Because——

Dr. BEMENT. Well, we thought——

Chairman BOEHLERT [continuing]. Those dollars, because if you don't get those dollars, then you have got to rearrange the priorities for your 16 million, it seems to me.

Dr. BEMENT. We have had excellent support from this Administration in supporting our response plan, as you well know, through our supplemental request, through our reprogramming request.

Chairman BOEHLERT. But that is only the beginning.

Dr. BEMENT. And that is only the beginning.

Chairman BOEHLERT. But are you operating under the assumption that the 16 million supplemental is the beginning? This is like chapter 1 and 2 and——

Dr. BEMENT. That will cover the investigation. That is correct.

Chairman BOEHLERT. And are you getting—you must have had at least preliminary discussions within OMB.

Dr. BEMENT. It is under very active considerations.

Chairman BOEHLERT. Yes. Right. Fine. And are you——

Dr. BEMENT. I am optimistic.

Chairman BOEHLERT. And you are optimistic. That is good. That is very important. Dr. Ehlers.

Mr. EHLERS. Thank you, Mr. Chairman. I wanted to address the same issue. This horrible, terrible tragedy that happened, and I wish it had never happened, has also given us an opportunity to really learn a great deal more about how to prevent such things, not, as you say, just from impact of an airplane, but from a blast. We, as a Nation, are susceptible to terrorist bombings, but also earthquakes, which is quite a different animal.

Dr. BEMENT. Yes.

Mr. EHLERS. It doesn't happen too frequently in New York, but many of the stresses that occurred would also be important in an earthquake situation, particularly the destruction of the sprinkler system, which is not too hard to imagine in earthquakes. I think it is absolutely essential that we do as much research on this as we can and that you have the resources you need to do that. Because something like this, thankfully, doesn't come along very often, and we can learn——

Dr. BEMENT. Yes.

Mr. EHLERS [continuing]. An immense amount about it. And also the point made, I believe, by Professor Corbett, that designing tall buildings is different than designing small buildings, and there are some basic facts we have to learn there. I am fascinated, for example, by the connections of the transverse beams, which seem totally inadequate in this situation, but obviously are adequate in the normal life of the building. We can learn a lot there. And I certainly encourage you to work as diligently as you can with the Administration to get whatever resources you need for this. And I am sure this Committee will be happy to support you in that effort.

Dr. BEMENT. Thank you very much, sir.

Mr. EHLERS. I have no further questions, Mr. Chairman.

WITNESS COMMENTS ON THE NATIONAL CONSTRUCTION SAFETY TEAM ACT

Chairman BOEHLERT. Thank you. Let me ask all of you the very obvious question. You have had my proposed bill for a few days to look at. Can you give us an instant reaction? Are there some voids there that you think we should address? Are there some things that we are trying to address that you think our wasting our time? Give us sort of an instant reaction to the proposed legislation. Let me start with Professor Corbett.

Mr. CORBETT. Yeah. I want to congratulate you on a very important bill. And I have been in the fire service for over 20 years now, and I can't think of a more important thing, as far as lessons learned, to have that kind of capability, you know, within our Federal Government, because these are national lessons. These are not New York City lessons. These are national fire service lessons that are going be learned, as well as many other things.

A couple comments that I had about it: I would suggest that perhaps some of the language that relates to the scope of the team, as far as specific types of disasters they would respond to. The word building failure, for example, was used in the proposed legislation. I think there are other issues or other situations where perhaps a building doesn't collapse or it doesn't fail in the sense that it falls down, but fails, perhaps, in a design concept. And let me give you a couple examples.

Several years ago there was a crowd crush incident in New York City. I believe it was at the City College where several students were killed at a concert at the base of a stairwell because they were going to this concert and the doors were not opened and they—and the doors opened out. And they were at the bottom of the stairwell trying to get in and the crowd crush behind them killed several people. I think that is an example of a kind of thing that NIST needs to look at, you know, in terms of building failures. Again, not collapse, but the design perhaps.

The other, I think, perhaps, even more important issue today is that, God forbid this should happen, but if we had a biochem attack in an existing high-rise building, I think it is important that the team would also respond to an incident like that. For example, if a terrorist would use some type of chemical or biological agent and released it through the heating and ventilation system, I think we would have to learn about what happened at that kind of incident as well. So if there is some way you can work with the language to accommodate that——

Chairman BOEHLERT. I guess it is a matter of definition. I mean, failure—we have got to have the broadest——

Mr. CORBETT. Right. And that is why I suggested back on March 6 that maybe calling it disaster, I think, would allow it to be much more comprehensive. And that is the other big thing I would encourage is that, again, not look at just the building, but what are the other issues—the fire fighting or the search and rescue or the other issues that will come up. And it is the comprehensive nature of that, as well. And by calling it disaster team, I think you get a little bit more of that, but it may be an issue for lawyers to deal with. I am not really sure, to tell you the truth. So——

Chairman BOEHLERT. Professor, let me assure you, you haven't heard the last of us. I mean, we are going to be in constant communication, because we value your input, and that is very important. I would ask that we refrain from any applause, although I love it. But the fact of the matter is this is very serious business and we are trying to be as professional and as unemotional as we can on a very emotional subject. But the witnesses are just so helpful to us as resources, and—well, you get the point. Dr. Bement.

Dr. BEMENT. Yes. I would say, first of all, I applaud the Committee with what it has done so far. I think it is serious and responsive. We have just received the draft of the bill. We are looking at it very carefully, and I would like to give my response in a much more thoughtful way. So I will work with you and the Committee as we go forward with this bill.

Chairman BOEHLERT. But you agree, for example, that you need the subpoena power.

Dr. BEMENT. I don't want to go there yet.

Chairman BOEHLERT. Is there a doubt in your mind? I do mean to put you on the spot on this one. I mean, there was some information, I think, that would have been of use, you know, the videotapes from the news outlets. For the life of me, I don't understand why they weren't cooperative when asked for them. Also the 911 tapes. I can think of a lot of things where subpoena power would have been very, very beneficial.

Dr. BEMENT. Yes.

Chairman BOEHLERT. But you feel you are constrained by your position that you——

Dr. BEMENT. I do feel somewhat constrained, but let me comment more openly. We have been in this position before in previous investigations. We found in previous investigations that we were able to operate effectively with those involved and we were able to get the information that we required. Furthermore, in this case, where we do have a Federal Advisory Committee—and I will say, in response to Dr. Corbett's comments that such a Federal Advisory Committee has already been scoped. We already have guidelines for that committee. We will be going out with the Federal Register very soon, soliciting comments and also specific suggestions for membership on that committee. So we will move just as quickly as we can on that.

Chairman BOEHLERT. But let me ask you, do you and Professor Corbett have a relationship?

Dr. BEMENT. No. But I have to say that most of the comments that he made in his testimony, I felt, were on target because there are procedures that we had anticipated. We have talked with a lot of groups and some of these suggestions have already been made, especially in some of the interest groups involved. And we have taken it very seriously. And I think almost everything that he commented on are things that we have——

Chairman BOEHLERT. I guess my point in asking that is I would hope that when the hearing is over and you shake hands and say "see you around," maybe there will be future telephone calls. We are thinking about this. What do you think?

Dr. BEMENT. Oh, you bet.

Chairman BOEHLERT. Okay. I mean——

Dr. BEMENT. I don't think there is any doubt about that. We will use the best minds we can find on this investigation.

Chairman BOEHLERT. Dr. Corley, what do you think about the draft legislation? Were there any voids? Do you think we are missing the boat?

Dr. CORLEY. Mr. Chairman, I do have a few comments on it, a few things that I think will improve it even more than it is already. First of all, my initial observation is that it addresses many of the things that we ran into, not just on this study, but having done others in the past, I always run into the same types of difficulties in getting information.

There is one item that was not clear to me, and that is whether or not the intent is to cover things such as earthquake, tornado, hurricane. Those types of building damage, as well as the fire and impact and the unexpected type of loads that were on this.

Chairman BOEHLERT. Well, we are still reviewing that issue. But my gut reaction would be, yes.

Dr. CORLEY. That is something that, I think, needs to be defined, whether it would or wouldn't cover those things. Then specifically when it comes to the composition of teams, there is some specific wording that I will be happy to share, but specifically, I think the team should be identified as having a minimum of ten experts on it—and this is from my experience in the past—and that these need to cover the areas of structural engineering, forensic engineering, and then, appropriately, fire protection engineering, geotechnical—those things that might have been related to the collapse. I believe that should be in the bill.

Chairman BOEHLERT. Thank you. Because that is so very important that we get input from respected professionals like you and the organization that you represent. That is what the whole process is all about. We are not the source of all wisdom up here.

Dr. CORLEY. And there is a fourth item that I would just like to mention at this time, and if you will permit me, after I have had time to read it more, I will no doubt have a few other suggestions.

Chairman BOEHLERT. Sure.

Dr. CORLEY. But in Section 4.3, there is some specific wording about what to do with code changes. And I think that will need a little bit of modification because it would require that the team come up with code changes without having the benefit of public input. And I think the appropriate way to do this is to come up with those areas and the substance of the code changes, then go out to the public to get their input so we can address those things that we technical people may not recognize. Those are just the first four items that I wanted to mention at this point.

Chairman BOEHLERT. Thanks. Professor Corbett, would you react to that?

Mr. CORBETT. You know, that is a very important issue is. The foundation of why we are doing this, is to make change in the codes. And that is such a critical piece that has to be looked at. I mean, that is a large issue of how we develop codes in this country. You know, we develop them privately. This is not developed by the Federal Government.

But there has got to be some type of very formalized relationship between the code-writing organizations and this very special construction safety team. Because I think the issues that come out of a disaster investigation are at a much higher level than the typical individual who goes before a code-writing organization to present a code change. This will be the work of a lot of people. And I recognize that the public input is certainly important, but I think there needs to be a fast track right to the code-writing organizations because these are issues that are looked at, again, by the most esteemed people that we can find for this team. So I think, again, that we need to treat it differently than the way we treat code changes today.

Chairman BOEHLERT. Mr. Shea, do you have any comments?

Mr. SHEA. Just real briefly. As a 25-year veteran of the Federal Government, what I did after the last hearing was to go and pull the NTSB authorizing legislation and then I visited the leadership of the NTSB as part of the process. My litmus test was very simple, which is that I asked them whether it worked, whether it gave them the range of authorities that they needed. They indicated to me that it did. I can see that the legislation you are proposing parallels that.

The only other thing I would add is that the issue of the coverage of the legislation, in terms of wind, earthquake, and other things, is certainly a subject of discussion in some of the communities out there right now. So I think it does appear to do what your intentions are.

The final thing I will say is it does, I see, is specifically call for the involvement of the U.S. Fire Administration. And I think that is an extremely important part of this effort to involve fire service professionals as we look at these issues.

Chairman BOEHLERT. You better believe it. Very, very important. And we used the NTSB model for our drafting purposes. The Chair is pleased to recognize Ms. Morella.

NIST BUILDING RESEARCH CAPABILITIES

Ms. MORELLA. Thank you, Mr. Chairman. I also want to thank the panel. Thank you for the excellent testimony you presented, the experience and commitment that is behind it too. Dr. Bement, I want to applaud NIST for its comprehensive effort in putting together a first-rate plan. I think that everybody on this Committee believes that NIST is the ideal agency for this research, and we will all work hard to ensure that you have the adequate resources for the study.

I would like to, in terms of the resources—Dr. Bement, the letters that you provided the Committee supporting NIST activities also support an additional $10 million to expand NIST large-scale fire facility to enable structural testing under fire conditions. Currently, this research capacity does not exist in the United States.

Dr. BEMENT. That is correct.

Ms. MORELLA. This research capacity is critical, it appears, to the development of advanced test measures, predictive tools, and performance standards. All three of these areas are highlighted by the BPAT as needing immediate work. So I would ask you, what are NIST's plans at this point?

Dr. BEMENT. At present, we have a two-pronged plan. We have begun immediately to do design studies of our existing fire facility to see how that might be expanded in order to help support the type of studies on large structural elements that we feel are essential.

But in addition to that, we also have an investigation worldwide to find existing facilities in Canada and the United Kingdom which might be available to us as we get into our research and development program should we not have an expanded facility in time. So we are going to do the testing one way or the other. But we feel it is absolutely essential for this Nation to have its own test facility that is adequate for these types of structural investigations.

Ms. MORELLA. You said that if you didn't—if you didn't get the necessary resources, you would reach out—what did you say, Canada——

Dr. BEMENT. In time.

Ms. MORELLA. In time. Uh-huh.

Dr. BEMENT. In time. Yes. We are looking at alternate approaches to do the testing that we feel would be essential for the World Trade Center.

Ms. MORELLA. And would that $10 million be part of that $41 million, or would it be over and above? When I say 41 million, I am talking about the 16 million plus another 25.

Dr. BEMENT. I will have to get back with you on that, Ms. Morella. The study—the design study is underway and I am not sure we have a definite number yet. But I will certainly respond to you on that question.

Ms. MORELLA. Good. We would like to know, you know, how that is going to be done. And, again, commend you. I think that NIST would be the very appropriate laboratory for this particular study.

I know a lot of the questions have been asked. I have some others, but could I ask each of you, is there anything that we have not asked you that we should ask you? Anything that Congress should be doing? We are going to be launching this bill that the Chairman has worked so hard on. Professor?

Mr. CORBETT. Yeah. I think the—well, I know the plan that we have got before us today is the way to go. You know, I think we need to get that team together very quickly, as I mentioned before. But as far as other things we need to be doing right now that is perhaps the most important thing, as Chairman Boehlert indicated, is to get moving on this, because there are issues about—you know, especially with the evacuation, that we need to contact people right away, and we need to have that plan in place. So I would just make the comment that, again——

Ms. MORELLA. Very good.

Mr. CORBETT [continuing]. Time is of the essence.

Ms. MORELLA. Very good. Mr. Shea, any final comments or, Dr. Corley? Everybody seems to be pretty happy. Dr. Barnett? Very good. Then, Dr. Bement? Well, thank you, Mr. Chairman.

Chairman BOEHLERT. Yes. I hate to do this, but we have a vote on. And we do want to come back because there are some more questions. And I hope you all would be able to stay. And with that, recess and be back after this vote.

[Recess]

NIST FUNDING OF THE INVESTIGATION

Chairman BOEHLERT. Can we resume deliberations, please? Ask a few questions—I have a few. To start with, we all keep referring to the $16 million. And I have a letter to me from the FEMA General Counsel that I want to put in the record that provides legislative language that is needed if FEMA is to transfer the money to NIST. As I have already said, I would rather appropriate the money directly.

But let me ask some questions about the way this has been set up in the Administration request. Mr. Shea, can you explain why the Administration has requested the NIST money through FEMA? This isn't to claim that this $16 million should count as money going to help New York City. Is it?

Mr. SHEA. Mr. Chairman, it is my understanding that what was done was that a number of different initiatives were collected by the Office of Management and Budget and packaged, in effect, like this. And I am not aware, although I have heard what you just said, about the money being packaged for the City of New York and the State of New York, but I am not aware of any direct conversations, certainly none that I have been involved in where that was the case.

Chairman BOEHLERT. But why couldn't they just request the money go directly to NIST?

Mr. SHEA. Well, there were discussions of that nature when the proposals first surfaced. And, of course, I talked to Dr. Bement about it as part of that process, and we did talk about different ways of doing it. The fact of the matter is, for whatever reason, it ended up in the FEMA appropriation. As I have said previously, there should be no concern or hesitancy. FEMA will transfer the funds when the funds are appropriated.

Chairman BOEHLERT. How quickly can you do it? Instantly?

Mr. SHEA. Within days. Normally, just procedurally, there is what is called a treasury warrant that is issued. And what I would seek to do is do actually what is called an appropriation transfer where both the funding and the authority goes directly to NIST and there would be no reporting relationship with FEMA as a result of that.

Chairman BOEHLERT. Is NIST getting anything in the supplemental, Dr. Bement?

Dr. BEMENT. Yes. There are other elements in the supplemental——

Chairman BOEHLERT. That go directly to NIST?

Dr. BEMENT [continuing]. That will come directly to NIST.

Chairman BOEHLERT. Can you help——

Dr. BEMENT. That is correct.

Chairman BOEHLERT [continuing] me understand why this wouldn't go directly to NIST? Why do we have this convoluted—what concerns me, I just hope there isn't lurking back there someone who is suggesting that this money somehow would count against the commitment to the City of New York for the recovery effort. No one is suggesting that. Are they?

Dr. BEMENT. Well, I am not going to assume that there wasn't a good reason. I just don't know what it was.

Chairman BOEHLERT. Okay. Okay. Well, the letter from FEMA to me says, "Any resulting codes and standards will not apply to the recovery efforts for this major disaster and are not particularly targeted to benefit the affected disaster area of New York City and the State of New York." That is sort of curious language. We are going to be following up on that.

The actual submission hasn't come to the Hill yet. Has it, for the supplemental?

Mr. SHEA. Yes, sir. It was transmitted to the Hill quite——

Chairman BOEHLERT. Is it? It has been. Okay.

Mr. SHEA. Quite a while ago now. Yeah.

Chairman BOEHLERT. Okay. Are you guys going to take a broker's fee or is the whole 16 million going to NIST?

Mr. SHEA. I assure you, Mr. Chairman, the entire $16 million will go to NIST.

Chairman BOEHLERT. The entire $16 million. And you expect it within days, not anything longer than days.

Mr. SHEA. Days is what I would predict at this point.

Chairman BOEHLERT. All right. Let me go to Mr. Shays because I will have a few more. One last thing, no strings attached?

Mr. SHEA. No, sir. As I said, my intention is to do what is called an appropriation transfer. It is a special mechanism used between Federal agencies. It means both the money and the authority go directly to the transferee, in this case, the National Institute of Standards and Technology. There are no strings on it. It is simply——

Chairman BOEHLERT. Will anyone have any objection if we weigh in with the appropriators and say this seems to be a sort of a silly way to do it. Why don't we just go directly to NIST? It wouldn't cause you any heartburn. Would it, Mr. Shea?

Mr. SHEA. No, Mr. Chairman. Not at all.

Chairman BOEHLERT. Okay. Well, I don't want to cause anybody heartburn. Mr. Shays.

FIRE AND BUILDING FAILURE

Mr. SHAYS. And, Chairman, if there was going to be a broker's fee, there certainly wouldn't be after you asked your question. You really covered the bases on that one. There was no angle that one would get around that one.

I have still a number of questions and we only have two. So I might come back after you, Mr. Chairman, and just do a few now. One of my concerns is that when the people went out of both towers, they went out in a fairly orderly way. In fact, it is pretty extraordinary from what I have read and the people I have spoken with—the respect that each had for the other as they tried to go down. Some people were slow; others carried them down, and so on.

But I think it is fair to say that they didn't quite think it would implode or collapse. And I would like to just have for the record, if it is accurate, that a building on fire isn't necessarily going to collapse within the first hour, and that these clearly were pretty extraordinary events. And my fear is that if we don't establish that for the record, we are going to have fires where people are just going to think they have to get out in the next 20 minutes and then no one gets out.

I would like to know—I mean, we do accept the fact that this was pretty extraordinary, correct? Nodding the heads doesn't get on the record.

Dr. BARNETT. Yeah.

Mr. SHAYS. Yes.

Dr. BARNETT. Yes. This was extraordinary. This was the first time that we had the collapse of a protected steel structure. And I think that is the whole point as we move ahead, and particularly with this proposed legislation, that we move ahead in a carefully planned approach, and we don't just change building codes because of one incident.

WTC BUILDING 7

Mr. SHAYS. Now, Building 7 is a building that, I guess, coincidentally, stayed standing for 7 hours. What did we learn about that building and why it was able to endure the fire for 7 hours? I would first like to know how it caught on fire.

Dr. CORLEY. I will address that question. First of all, in discussing with the New York City Fire Department, we determined and concluded that it started on fire after or as Building 2 collapsed, that there was debris from that building that was propelled into Building 7 and that the fire started at that time.

Mr. SHAYS. And in some cases that debris could have had aircraft fuel on it and so on. Were these lighted timbers that——

Dr. CORLEY. No. We think it was building contents that was propelled over there.

Mr. SHAYS. Okay.

Dr. CORLEY. That by the time Building 2 collapsed——

Mr. SHAYS. Okay.

Dr. CORLEY [continuing]. The aircraft fuel would not have——

Mr. SHAYS. Okay.

Dr. CORLEY [continuing]. Been there anymore. It would have been consumed by that time. Then, from that point on——

Mr. SHAYS. And how tall a building?

Dr. CORLEY. It is 47 stories——

Mr. SHAYS. Wow.

Dr. CORLEY [continuing]. For Building 7. It is a big building. The fire that we were able to follow from that point on was throughout the building, but it was particularly of long duration in the lower floors around where the very large transfer elements, trusses and beams and columns, were located. This building had to be built with a very random spacing of foundations because of what was there before it.

Mr. SHAYS. Was it a pretty traditional type building, unlike the two towers?

Dr. CORLEY. Above the transfer area was a very traditional building. At the transfer area in the lower floors, over the substation for Com-Ed, it had these enormous trusses that took the loads and brought them to the columns. That is the area where the fire burned for a long period of time, and it does result in one of our recommendations. And that is for key elements of that where the collapse of an element might result in the collapse of an entire building. We recommend that they be reviewed to see if they should have longer fire duration for those elements than would be necessary in the rest of the building.

Mr. SHAYS. And now, my understanding is, in the case of Building 7, there was no water pressure because of the breaking of water mains and so on, with the collapse of the towers. Is that correct?

Dr. CORLEY. That is what we determined. That it, Building 7, collapsed prior to the time they were able to get the water pressure back up to higher levels. They didn't really get it up to normal levels, but at least got some water pressure back.

Mr. SHAYS. And the water we were taking out of the Hudson River, we were trying to put into the debris on the towers to try to get people out, get them out alive.

Dr. CORLEY. Yes.

Mr. SHAYS. So what we have, though, is this incredible case study. When do you burn a 47—when do you allow a building 47 stories tall to just burn until it collapses? So there are tremendous lessons to be learned about structures from these buildings in particular.

Dr. CORLEY. Yes. We put a great deal of emphasis on Building 7 in our report, and we conclude that we have an understanding, we believe, of how it performed, but that we need to pin down what the source of fuel was that allowed it to burn that long.

Mr. SHAYS. Now, I don't know the answer to this question. But, maybe I should. How many people, it is thought, were killed in that building. Did most get out?

Dr. CORLEY. We were not able to determine that there were any fatalities in that building. There may have been, but we could not determine that there were.

Mr. SHAYS. But minimal compared to, obviously, elsewhere.

Dr. CORLEY. Yes.

Mr. SHAYS. And so that should be some reassurance to people if they are in a building, a more typical building on fire, that they do have time to get out of the building.

Dr. CORLEY. Oh, yes. We believe that without the damage that occurred to the two towers, that buildings will perform—will stand up for a significant period of time without collapse, with the fire requirements that are there now.

Mr. SHAYS. Now, are you able to determine if you did have proper water pressure and so on, whether that you could have prevented the fire from consuming the building?

Dr. CORLEY. We looked into that, discussed it quite a lot. And while we did not make a strong statement in the report—it was really beyond the scope of what we were doing—we do believe if it had been fought, they could have put it out, and if they could have put it out, that there would not have been that risk of collapse to that building.

Mr. SHAYS. Now, I have a particular bias that the actions against us weren't criminal acts, they were acts of war, acts of terror. And I kind of bristle when I think of our treating this as a criminal act in which we have to prove, beyond a shadow of a doubt, that someone did it and they were at the scene or whatever you need to deal with in a crime. But there are—I have constituents who are interested in knowing, given that it is technically a criminal site. I have constituents who are interested to know how we can justify beginning to build on that site. Is it that all the debris is entirely taken away and so therefore there is no evidence at the site that is helpful?

Dr. CORLEY. I am not an expert in the legal side of it, but you are, indeed, correct, that the debris will soon have been all removed and that there would not be a substantial amount of information there that I would anticipate would be useful in any trial.

Mr. SHAYS. Sir, I want to—and since there are only two of us, do you want me to go? Or do you want to go and then I will come back. I have about 10 more minutes of questions at the most, then I will be done.

Chairman BOEHLERT. Okay. All right. Let me go. Just a couple very——

Mr. SHAYS. Can I just say, Mr. Chairman, that your staff has written some incredible questions that I do think we need to put on the record. And I hope you don't underestimate the value of your great staff.

NIST FOLLOW-UP INVESTIGATION

Chairman BOEHLERT. I never underestimate the value of the staff. Dr. Corley, as far as you know, do the NIST plans for the follow-up investigation and research cover the areas you highlighted as needing further work?

Dr. CORLEY. I have reviewed their plan and have concluded that they are covering the majority of the things that we have recommended in the report. My belief is they intend, in the overall program, to include all of them, and have put priorities to include the ones that they consider most important first.

Chairman BOEHLERT. What would you—what is missing?

Dr. CORLEY. I don't think there is anything missing in the full program, presuming that gets done. In the early stage of the program, there are a couple of areas that could have heavier emphasis, just to be sure that they get done in case the program doesn't get carried out.

Chairman BOEHLERT. Have you had additional input into the plan after you have seen the initial plan? I mean, have you said, now, look at—NIST, we think that you should give a higher priority to this, more emphasis on this? Have you had an ongoing dialogue?

Dr. CORLEY. The dialogue has been started and we hope to have continual dialogue as the program gets finalized.

Chairman BOEHLERT. And, Dr. Bement, would you concede that maybe this added input would be valuable? Have you talked this thing through, and Dr. Corley may say, we think you are missing the boat on this one. Why don't you give more emphasis? And then you talk it through and maybe you would agree with him and maybe you wouldn't. But I mean——

Dr. BEMENT. Our plan is still malleable. It changes. It will probably change some more. I am sure that when we have our public hearing in New York and get further input on our plan, it will change still more.

Chairman BOEHLERT. Can you give us some indication on how you decided what you would include, what you wouldn't, how you prioritize? And then also, I would like to know the central goal of the investigation.

Dr. BEMENT. I think going back to the central point, why these were unique incidences and why collapse occurred, there have been instances where buildings have had major fires that have burned to completion without the buildings collapsing. I mean, there are several such incidents on record. I think in this particular instance, because of the singular nature of the collapse and the effect of the fire on that collapse, we really have to understand that in much better detail. And so that is, far and away in our minds, the most critical thing to understand first; and then begin to anticipate what type of technical basis we are going to have to develop in order to bring about code changes in buildings that may be subjected to either blast or terrorist attack of one kind or another.

In addition to that, of course, we are very much concerned that firefighters have all the access that they need and all the tools that they need in fighting fires in tall buildings. And, of course, communications have been mentioned, but protective clothing is another issue. Having access to the fire is another issue—not being blocked in trying to enter a building and do the work that they have to do. So I would say that we consider that to be a very essential part of our early investigation.

Now, there are a lot of other elements that are also critical, and that has to do with the behavior of connections under fire, the behavior of open truss structures under fire, that are central to understanding in detail just the exact sequence of the events that led up to the collapse. We think that also is essential to do early.

So our initial attention is on Buildings 1, 2, and 7, but the lessons learned from that part of the investigation will apply broadly to other buildings as well because these elements are in general use in——

Chairman BOEHLERT. But shouldn't the Bankers Trust be reviewed, because that is more typical of what might be expected to happen.

Dr. BEMENT. Well, in the case of Bankers Trust, there is no mystery about what the initiating event was. It was the collapse of the World Trade Center buildings and the debris that came from the World Trade Center buildings. Now, you are absolutely right in your understanding of how that impact was absorbed and how it was dampened and also the pathways in which the load was propagated through the building. That has to be subjected to finite element analysis and further testing.

And those are the specific tests that will be part of the research and development program, a lot of which, incidentally, will be done in parallel with the investigation. So it is not as if it is being overlooked.

Chairman BOEHLERT. Finally, and this seems like an appropriate way to wind up. I want to be sure we all understand what is at stake in terms of building safety, in terms of the results of these efforts we have been talking about today.

BUILDING CODES/CODE-RELATED RESEARCH

Dr. Corley, what changes in codes and research related to codes is the highest priority in following up on your investigation? You know, obviously we are not going to design against planes hitting buildings at high speed. What changes can we design for?

Dr. CORLEY. The items that we saw that need the most attention, other than those that deal strictly with buildings that can be identified as potential targets for terrorists, are those dealing with the fire resistance of connections. That was the one. Also related to that is the amount of fuel that is in a building and there is a need to look into that the fuels that go into buildings today are different than they were at the time the——

Chairman BOEHLERT. That is your highest priority?

Dr. CORLEY. Those are the two highest priorities—the connections and the amount of fuel.

Chairman BOEHLERT. Okay.

Dr. CORLEY. And——

Chairman BOEHLERT. Dr. Barnett.

Dr. BARNETT. Thank you. I would like to add something about the connections. In Building 5, we had major collapses due to connection behavior in the fire. That is why it is a priority. Building 5's construction was similar to buildings around us every day.

Chairman BOEHLERT. Uh-huh.

Dr. BARNETT. We need to look into this. We talked about building codes. This may or may not result in a building code change. It certainly, in my opinion, will result in a design practice change. Design practice by professionals can occur at once. As soon as professionals realize there is an issue, they can make the change. Building codes are minimum standards. It is really not where we ought to be heading, or at least just not that alone. We need to look at the whole picture.

But Building 5 was a normal building and it had a fire and it had major collapses. This has never happened before. We need to understand why. And I think that is why Dr. Corley has identified the connection issue as a very significant issue.

Chairman BOEHLERT. But the changes are very important and I am glad you have pinpointed that. Because when all is said and done and we come up with model codes, but no one is forced to do anything to put those codes into practice. Is that correct?

Dr. CORLEY. The code process is that model codes are put together and then the local jurisdictions have to adopt them. And while they are not forced to do that, there is wide adoption of those codes. So——

Chairman BOEHLERT. But they are not mandates.

Dr. CORLEY. They are not mandated to adopt those codes. And, in fact, when the local jurisdiction adopts one, they can even make exceptions——

Chairman BOEHLERT. Uh-huh.

Dr. CORLEY [continuing]. To the code. But in practice, once it goes into the model code, it is unusual for a local jurisdiction not to pick it up.

Chairman BOEHLERT. Dr. Bement, would you agree with Dr. Corley's priorities?

Dr. BEMENT. Yes. I think it is very consistent with what I said earlier, that we do want to pay particular attention to connections and also the fire resistance of these connections. I think his point on fuel loading in buildings is a point that I made earlier in my testimony. We feel very strongly about that.

Chairman BOEHLERT. Well, how come Building 5 isn't part of your investigations then?

Dr. BEMENT. Building 5 is part of the research and development program. We want to actually do tests on the connections to understand the failure modes. And it is not being overlooked.

Chairman BOEHLERT. But is there any money for that? R&D, I mean.

Dr. BEMENT. We will have money in our '03 request if it is passed.

Chairman BOEHLERT. Well, we are talking about intentions rather than reality. All right. Mr. Shays.

NIST SUBPOENA POWER

Mr. SHAYS. Thank you, Mr. Chairman. Think of me as the PS here, Mr. Chairman. I said think of me as the P.S. at the end of your final questions. I have some questions that some of my constituents have a particular interest in. And like New York City and Long Island and New Jersey, 60 constituents in my district, the 4th Congressional district, lost loved ones.

With regard to the subpoena power, Dr. Bement, that you didn't seem to advocate, I am really unclear as to what your position is.

Dr. BEMENT. Well, I didn't——

Mr. SHAYS. And let me just finish.

Dr. BEMENT. Sorry. Yes.

Mr. SHAYS. Yes. I can't imagine taking—I am expressing a bias, but I want to at least warn you of my bias. I can't imagine taking seriously any investigative organization that doesn't have the power to demand information when they need it. Otherwise, you are going to get the information that people want you to have, not necessarily information you need to have. That is my bias. And I would like to know what you——

Dr. BEMENT. I don't want anyone on the Committee to conclude that I made a specific statement for or against the subpoena power at this time. As long as it is under active consideration, it is very difficult for me to characterize what the position of the Administration would be.

Mr. SHAYS. Fair enough. I will leave it at that. I mean, so it is not that you oppose it. It is that the Administration hasn't yet made up their mind.

Dr. BEMENT. I would like to leave it there. Yes. I would agree with that.

Mr. SHAYS. Okay. So we need to get the Administration to weigh in on this. That is not your responsibility. That would be ours. With regard to a testing facility, are there testing facilities overseas that we could utilize and could we have our own facility?

Dr. BEMENT. Well, there is one actually in Canada that we could use. So it is not that far away.

Mr. SHAYS. Is that a possibility?

Dr. BEMENT. Yes.

Mr. SHAYS. Okay.

Dr. BEMENT. We have already entered into discussions.

Mr. SHAYS. All right. What role is ASCE going to play in the investigation?

Dr. BEMENT. Well, first of all, let me establish the principle that NIST will do an independent and objective investigation and we will stand behind our findings and recommendations. We will, of course, engage individual experts, many of whom will be members of ASCE, as well as other professional societies and the academic community at large. So we are not, at this stage—and it could very well be that some members will be part of our Federal Advisory Committee. So at this point, we don't see a formal relationship in the investigation, but we could very well have a formal investigation in the follow-up research and development program.

BUILDING PERFORMANCE INFORMATION REPOSITORY

Mr. SHAYS. Thank you. Is there a repository for building performances, prior studies of building failures, either from natural disaster or human error in the design of the building, or, a malicious attack or something? Does such a repository of information exist anywhere?

Dr. BEMENT. Yes, sir. NIST has a building and fire information system that has a general knowledge base on past investigations, past events, technology developments, codes, etcetera. All the information that we will collect and even all the reports that we will generate as part of the investigation will be part of that information system. And that is available to the public in general. And I think, going forward, as we continue to be involved in these types of disasters or these types of investigations, they will also be a part of that repository.

Mr. SHAYS. Does that include NSF and BPAT investigations as well in the past?

Dr. BEMENT. I would have to consult with—not yet, I am told.

Mr. SHAYS. Okay. Is this something that the general public is able to turn to as a resource?

Dr. BEMENT. I think it is on our website. Yes. It is on our general website.

Mr. SHAYS. But it is not as complete as it could be. And so there will be an attempt to make it more complete and then also provide it to the general public?

Dr. BEMENT. Yes.

Mr. SHAYS. Mr. Chairman, let me just conclude by just making a comment: in Bridgeport, we lost 29 workers when they were putting up a lift slab at L'Ambiance, and it was determined that the lift slab method was not a very safe way to do it. I mean, you literally molded each one and then you lifted each floor up. And workers were in down below as they kept lifting up the other floors.

And what the Bush Administration actually did—it was under the Bush Administration—they set up an office of construction safety within OSHA and promulgated new regulations to protect workers. I mean, we learned a great deal from that experience. And I would imagine that we are going to learn a ton of information.

And I have to say to you that when I attended your first hearing, I was really wondering, what is the point? I mean, you have two planes go into a building. But this is a wealth of knowledge that you are so right in making sure, and others obviously, that we pursue.

And obviously the victims who have suffered from this, I think, also deserve to know that we will learn a lot and that their loved ones will—that some good things will happen from this horrific event, that we learn things that can save lives in the future.

And so I just really appreciate what the gentlemen here are doing. I appreciate what many in your audience have done, because they have been catalysts for this effort as well. And, thank you.

Chairman BOEHLERT. Thank you very much, Mr. Shays, particularly for your attentiveness and active involvement. And I want to thank all the witnesses, but particularly Dr. Corley and ASCE. You have given countless hours, and it is not over yet, on something that is very important for us all.

I want to remind everyone that there is going to be a press availability in Room 2325. The witnesses and the members of the Committee who are—oh, it is going to be right here? It is going to be right here. See how flexible we are? We can adjust.

We will have a press conference next week to announce the introduction of the bill. We are still working it and we are getting suggestions. We are very open to any good ideas that will come along. But we intend to really pursue this to its logical conclusion in short order.

And I want to remind NIST, Dr. Bement, that we are going to help you get that $16 million and hope we can avoid the convoluted path that some have charted for it. We would like to get it directly for you.

And I can appreciate it sometimes. It puts someone like you in a difficult position, some of the questions we ask, because obviously the Administration is weighing various policy options. But we are going to get you subpoena power because we think it is very important. And we are going to get you the resources because we think that is very important.

Dr. BEMENT. Thank you very much.

Chairman BOEHLERT. And on behalf of the entire Committee, I want to thank all of you for spending so much of your time—just not today, but throughout this whole process—thank you for being very candid, particularly Professor Corbett. I like your style. Thank you very much. This hearing is adjourned. Yeah. Now you can clap.

[Whereupon, at 3:31 p.m., the Committee was adjourned.]

Appendix 1:

ADDITIONAL MATERIAL FOR THE RECORD

Federal Emergency Management Agency
Washington, D.C. 20472

April 30, 2002

The Honorable Sherwood Boehlert
Chairman
Committee on Science
U.S. House of Representatives
Washington, D.C. 20515

Dear Mr. Chairman:

It is the opinion of the Office of General Counsel that additional authority is necessary for FEMA to transfer funds from the Disaster Relief Fund to the National Institute for Science and Technology (NIST), U.S. Department of Commerce, to conduct a comprehensive building assessment of the World Trade Center (WTC). I understand such funding is proposed to be provided through a supplemental appropriation to the Disaster Relief Fund.

The authorized purposes of funds appropriated to FEMA's "Disaster Relief Fund" (DRF) are to carry out disaster relief activities under the Robert T. Stafford Disaster Relief and Emergency Assistance Act (Stafford Act), 42 U.S.C. 5121-5206. Disaster relief activities under the Stafford Act primarily include emergency protective measures, repair and replacement of public infrastructure, and hazard mitigation. In addition to these disaster relief activities specifically authorized under Title IV of the Stafford Act, "necessary expenses" to carry out our disaster response, recovery and mitigation purposes are authorized, including, for example, the funding of disaster offices, staffing, administration and technical assistance costs directly associated with implementing our disaster assistance programs. See Appropriations Law, GAO, 4-14 *et seq.* (2nd Ed. 1992.) Other activities, as well as those under more specific authorities of other Federal agencies, are generally not authorized. Id. at 6-103.

NIST proposes to conduct a National Building and Fire Safety Investigation of the WTC to assess the technical causes of the building failure and to identify building and fire codes and standards that should be considered for revision by the building industry nationally. This may include multi-year research, development, and dissemination efforts to provide a technical basis for such changes to building and fire codes and standards and engineering practices. Such an in-depth, technical investigation goes well beyond the scope of the building performance assessments conducted by FEMA following major disaster declarations, and, moreover, is within NIST's existing legislative authorities at 15 U.S.C. 281a. See Statement of Dr. Arden L. Bement, Jr., Director, NIST, U.S. Dept. of Commerce, before the U.S. House of Representatives Committee on Science (March 6, 2002).

In this case, the investigation proposed for NIST funding is intended for comprehensive and long-term identification, development, and encouragement of future building codes and standards and engineering practices nationally. Any resulting codes and standards will not apply to the recovery efforts for this Major Disaster, and are not particularly targeted to benefit the affected disaster area of New York City and the State of New York. Such a long-term effort with national scope is not a disaster relief activity within the Stafford Act and is not a necessary expense of providing disaster relief under the Stafford Act for this Major Disaster. In addition, FEMA appropriations would typically not be available to augment the appropriations of NIST when its own authorities are more appropriate to the specific purposes of the activity.

As you are aware, the Bush Administration has expressed a strong commitment for the NIST assessment of the WTC buildings and has requested $16 million as part of the FY 2002 supplemental budget request to support the NIST investigation. This aspect of the President's budget request, if appropriately enacted with respect to FEMA's DRF appropriation, would provide FEMA authority for the funding of the study.

Therefore, in order for FEMA to transfer funds appropriated to the DRF through the proposed supplemental appropriation, we would expect language authorizing the use and the transfer in the text of the supplemental appropriation law. Accordingly, FEMA has raised with the House Appropriations Committee staff the potential inclusion in the appropriation for the Disaster Relief Fund of language such as the following:

> *Provided*, that $16,000,000 shall be transferred to the National Institute of Standards and Technology to conduct an assessment of building construction standards connected to the collapse of the World Trade Center and related studies.

Should the supplemental appropriation pass with the inclusion of such or similar language to reflect the President's supplemental request for funding for the WTC investigation, FEMA would have adequate authority to make timely transfer of the funds to NIST.

Thank you for your attention to this matter.

Yours Truly,

Mark D. Wallace
Deputy General Counsel

Cc: The Honorable Barbara A. Mikulski, Chair, Subcommittee on Veterans Affairs, HUD, and Independent Agencies, Committee on Appropriations, U.S. Senate
The Honorable Christopher Bond, Ranking Minority Member, Subcommittee on Veterans Affairs, HUD and Independent Agencies, Committee on Appropriations, U.S. Senate
The Honorable James T. Walsh, Chairman, Subcommittee on Veterans Affairs, HUD and Independent Agencies, Committee on Appropriations, U.S. House of Representatives
The Honorable Alan B. Mollohan, Ranking Minority Member, Subcommittee on Veterans Affairs, HUD and Independent Agencies, Committee on Appropriations, U.S. House of Representatives

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DIRECTOR'S OFFICE
NIST

2002 JAN 28 P 2:13

January 24, 2002

Dr. Arden L. Bement, Jr.
Director
National Institute of Standards and Technology
100 Bureau Drive Stop 100
Gaithersburg, MD 20899-1000

Dear Dr. Bement:

As requested, I am writing to you to express our support of the National Institute of Standards and Technology, United States Department of Commerce, in its effort to conduct a technical investigation of the building and fire safety issues related to the World Trade Center disaster.

On January 10, 2002, three of our key staff attended a meeting with Dr. S. Shyam Sunder, Chief of the Structures Division at NIST, and with other representatives from local authorities in New York City. During this meeting Dr. Sunder briefed us on NIST, its Building and Fire Research Laboratory, and the comprehensive public-private program planned in response to the events of September 11, 2001. He also shared with us the preliminary plans for the technical investigation, including the use of an independent technical review panel composed of leading practitioners and academic experts to guide the investigation.

Based on my understanding of the presentation, I believe that NIST is the appropriate federal agency to conduct this investigation to create new technical and/or scientific knowledge. The Port Authority of NY & NJ will assist NIST in this effort and will participate to the extent that we are able. *It is our understanding that no part of any report resulting from such investigation shall be submitted as evidence or used in any suit or action for damages arising out of any matter mentioned in the report. Furthermore, anyone working on this investigation will not be able to act as an expert witness* Please confirm that our understanding of the above is accurate.

I believe that the findings and recommendations of this work will be extremely valuable to the building and fire safety communities and to the future safety and well being of the American public.

Sincerely,

for Francis J. Lombardi, P.E.
Chief Engineer

cc: Joe M. Allbaugh, Director, Federal Emergency Management Agency
Robert Shea, Acting Administrator, FEMA Federal Insurance and Mitigation Division

Statement of

International Code Council (ICC)

On

"The Investigation of the World Trade Center Collapse: Findings, Recommendations and Next Steps"

Submitted for the record of the hearing before the
Committee on Science
U.S. House of Representatives
May 1, 2002

Sara C. Yerkes
Government Relations Director
May 14, 2002

The International Code Council (ICC) appreciates the opportunity to submit this written statement into the record of the hearing on "The Investigation of the World Trade Center Collapse: Findings, Recommendations and Next Steps," held on May 1, 2002 by the House Science Committee.

Comments on the proposed legislation "National Construction Safety Team Act" will be submitted under separate cover to all members of the House Science Committee.

Comments on Findings and Recommendations

The engineers who studied the progressive collapse of the World Trade Center reported that the force of the airplanes as they impacted the towers was not sufficient to cause the towers to collapse. The towers were robust and the fact that they withstood such a tremendous impact was impressive. The American Society of Civil Engineers (ASCE) states in its testimony that ". . . the ability of the two towers to withstand aircraft impacts without immediate collapse was a direct function of their design and construction characteristics . . ." Even if the towers were not able to resist the combination of the structural damage and the fires ignited by the huge load of jet fuel, it was the ability of the towers to withstand the impact for as long as they did that enabled so many people to evacuate. This is a credit to the building codes and design practices currently used in the United States.

Teams of engineers and professors are studying what other countries are already implementing. Some countries in Asia are using features that provide redundant structural and firefighting protections such as reinforced concrete cores with dedicated refuge floors every 15 levels. Refuge floors are not furnished and are fireproof to provide safe harbor to people during an evacuation. And, The Tall Buildings and Urban Habitat (TBUH) has been testing ideas for emergency evacuation. According to an article written by Mary Lou Luif, Senior Staff Editor of BOCA International, Inc., some of the concepts under review include skybridges to adjacent buildings, rooftop helipads, and additional stairwells.

The FEMA/ASCE Performance Study Team recommends that further study be done into the collapse of the buildings, which could potentially lead to revisions in both building codes and design practices.

Although the codes can require more concrete, more flexible piping systems, thicker fire walls, or even provide built-in redundancy so that if one system fails another will withstand, the question arises whether the codes would ever be able to protect buildings against malicious scenarios such as acts of terrorism or war. The code development community has begun deliberating and considering all of the options available, cautiously analyzing the technical, economical, and human factors associated with the feasibility of strengthening buildings.

ICC Support

ICC supports the National Institute of Standards and Technology (NIST) response plan and looks forward to working closely with that agency.

ICC is a unique organization with expertise in all aspects of building design and construction. Our staff of 360 and 45,000 members includes all engineering disciplines, architects, code officials, building, plumbing, mechanical and fire inspectors, elected officials, builders, building owners and managers, advocates for the disabled community, and many others. In addition to the vast knowledge brought forth by these individuals, the ICC statutory members share nearly 200 years of collective experience in developing the model codes used throughout the U.S.

There are more than 16,000 code officials working in communities throughout the U.S. ICC estimates code officials conduct nearly 43,000 site inspections to new and existing facilities each day. The U.S. has the most effective system of building inspections and code enforcement in the world.

ICC is the developer of the International Codes™ used throughout the U.S., and is the organization that represents the state and local government code officials who enforce these building codes. As such, ICC is disappointed that code officials have been noticeably left out of the process as hearings are being held and legislation is being considered on homeland building security that may impact building codes.

Ultimately it is organizations such as ICC that will address how emerging public policies must be incorporated into the codes, implemented by the jurisdictions and enforced at the state and local level. In the words of FEMA, ". . . code officials are the first line of defense." ICC urges Congress to include code officials in its deliberations on all matters pertaining to building safety.

Code Development in the United States

Construction in the U.S. is a sophisticated process governed by codes and standards that regulate building, plumbing, gas, mechanical, electrical, energy, fire, accessibility and other specialized aspects of construction. The code development process is a dynamic process involving constant interaction between the private and public sectors of the construction industry, Federal, state and local governments.

The code development process in the U.S. is a private sector activity. ICC is a fully self-supporting nonprofit organization. The revenues used to develop and publish the codes are generated from its member organizations.

The code development process used to develop the International Codes is known as a governmental consensus process. It is an open, inclusive, and balanced consensus process with built-in safeguards to prevent domination by any single interest.

Model construction codes are developed to be adopted by reference into Federal, state or local laws. They are developed in the same manner as local governments are required to develop laws. It is a transparent and open process. There must be a guarantee of fairness in the process, of no conflicts of interest, and with no vested economic interest in the outcome of the final vote. The code officials represent local government agencies and their interest is the safety and well being of the public. The process incorporates a number of checks and balances to ensure the final documents are of the highest quality and reflect the latest technology.

This system of code development has ensured the citizens of the U.S. the highest level of building safety in the world as witnessed by the performance of the World Trade Center.

Participants in the process include code officials, other government regulatory agencies, academia, building owners, insurance companies, builders, manufacturers, testing laboratories and others. Participation in the ICC code development process is encouraged and is open to all groups and individuals.

Enforcement of Building Regulations

The enforcement of building regulations in the U.S. is the role of state and local government. This enforcement authority is derived from the 10th

Amendment of the U.S. Constitution, which gives states the right to legislate for the protection of the public health, safety, and welfare.

The family of International Codes developed by ICC includes building, fuel gas, energy conservation, fire, mechanical, plumbing, property maintenance, private sewage disposal, residential construction, zoning, urban-wildland interface, existing buildings, and a performance code. When a community adopts the International Codes it also benefits from the expertise of hundreds of technical staff, as well as established services that support the codes such as training and certification programs.

In a study conducted by the Federal Trade Commission (FTC) in 1988, approximately 97% of cities, counties and states that have adopted and are enforcing building and safety codes are using documents developed by the statutory members of ICC. For more information on the International Codes adoptions by state or local jurisdictions, please visit the ICC website at www.intlcode.org.

The International Codes unified system provides substantial benefits to stakeholders who can now work with a consistent set of requirements throughout the United States. A unified system enhances economic development through the utilization of state-of-the-art technology in materials research, design and construction practices. A streamlined building regulatory system through a single family of codes brings consistency and compatibility to multiple layers of requirements existing at all levels of government. One system permits manufacturers to put their efforts into research and development, thus advancing innovation through performance based provisions that require consistent and predictable levels of building performance and safety.

OMB A-119 and PL 104-113

In 1996 the House Science Committee had the wisdom to pass the National Technology Transfer and Advancement Act (NTTAA), PL 104-113. PL 104-113 codified the OMB Circular A-119, Federal Participation in the Development and Use of Voluntary Consensus Standards and in Conformity Assessment. The law directs Federal agencies to move toward using voluntary standards rather than agency-unique standards and encourages the participation and interaction with private-sector voluntary standards bodies. NIST serves as chair of the Interagency Committee on Standards Policy (ICSP).

ICC supports this government policy. For many years the standards developing organizations have been encouraging Federal agencies to increase their participation in the private sector voluntary standards development processes. It is a logical, efficient, and cost effective way for the Federal government to establish standards that serve national needs.

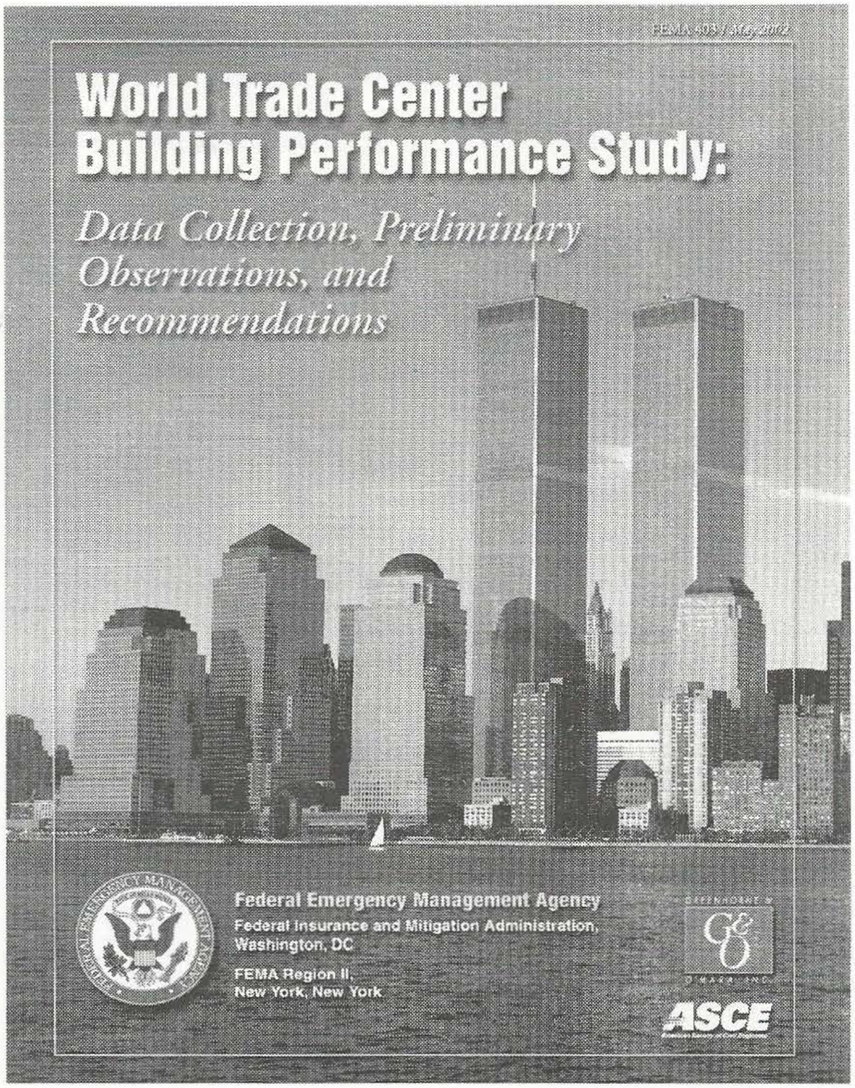
In summary, ICC is committed to a safe and strong built environment. The code development process serves the public best as a private sector activity, leaving the enforcement of the building and safety codes under the jurisdiction of state and local governments.

ICC respectfully makes the following recommendations to the House Science Committee:

1) Include the building code community in homeland security and building safety deliberations;
2) Continue supporting the national, private-sector development of codes and standards; and
3) Encourage all Federal agencies with a stake in building construction and safety to get involved in the code development process.

Thank you again for the opportunity to submit this statement. ICC would be pleased to provide additional information or to respond in more detail to any questions from the Committee.

I may be reached at 703-931-4533, ext 12 or by email: yerkes@intlcode.org



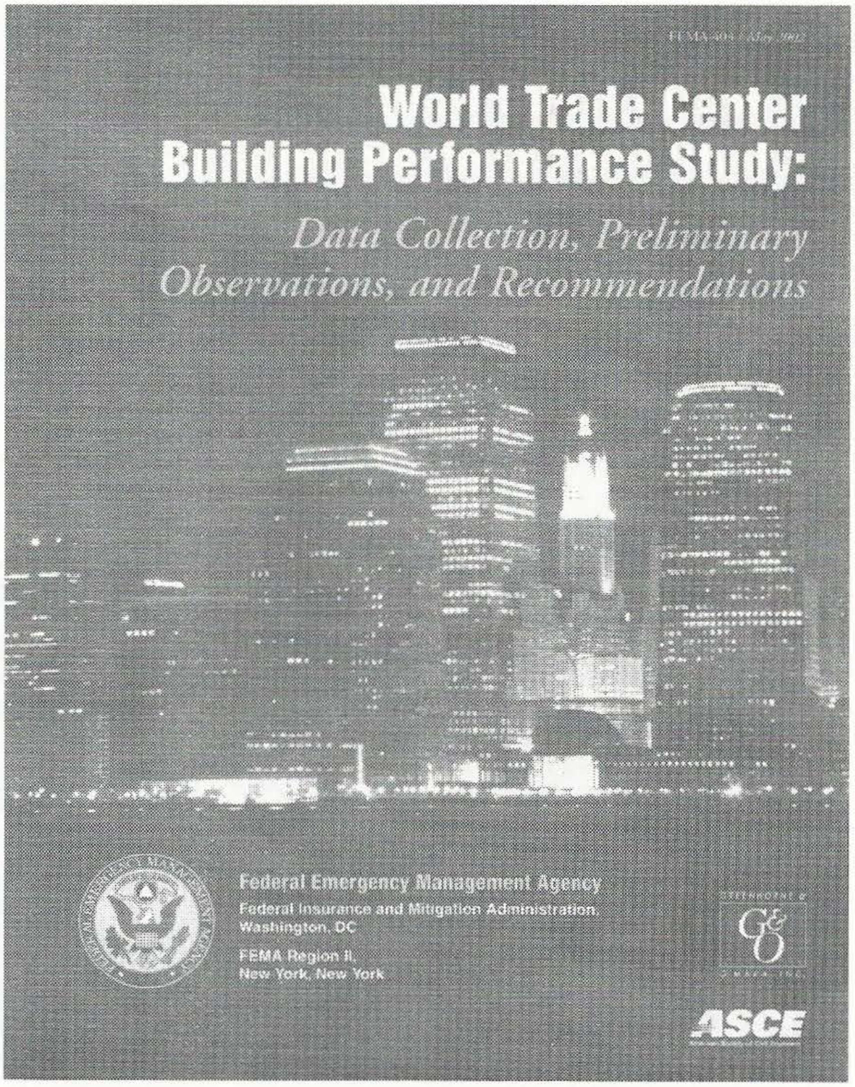
FEMA 403 / May 2002

World Trade Center Building Performance Study:

Data Collection, Preliminary Observations, and Recommendations

Federal Emergency Management Agency
Federal Insurance and Mitigation Administration,
Washington, DC

FEMA Region II,
New York, New York



FEMA 403 / May 2002

World Trade Center Building Performance Study:

Data Collection, Preliminary Observations, and Recommendations

Federal Emergency Management Agency
Federal Insurance and Mitigation Administration,
Washington, DC

FEMA Region II,
New York, New York

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Table of Contents

Executive Summary

1 Introduction

1.1 Purpose and Scope of Study 1-1

1.2 WTC Site 1-2

1.3 Timeline and Event Summary 1-4

1.4 Response of the Engineering Community 1-8

- 1.4.1 Local Authorities 1-8
- 1.4.2 SEAoNY Participation 1-10

1.5 Overview of Building Codes and Fire Standards 1-15

- 1.5.1 Building Codes 1-15
- 1.5.2 Unusual Building Loads 1-16
- 1.5.3 Overview of Fire-Structure Interaction 1-17
  - 1.5.3.1 ASTM E119 Standard Fire Test 1-18
  - 1.5.3.2 Performance in Actual Building Fires 1-18

1.6 Report Organization 1-20

1.7 References 1-21

2 WTC 1 and WTC 2

2.1 Building Descriptions 2-1

- 2.1.1 General 2-1
- 2.1.2 Structural Description 2-1
- 2.1.3 Fire Protection 2-11
  - 2.1.3.1 Passive Protection 2-12
  - 2.1.3.2 Suppression 2-12

2.1.3.3 Smoke Management 2-13
2.1.3.4 Fire Department Features 2-13
2.1.4 Emergency Egress 2-13
2.1.5 Emergency Power 2-14
2.1.6 Management Procedures 2-14
2.2 Building Response 2-15
2.2.1 WTC 1 2-15
2.2.1.1 Initial Damage From Aircraft Impact 2-15
2.2.1.2 Fire Development 2-21
2.2.1.3 Evacuation 2-24
2.2.1.4 Structural Response to Fire Loading 2-24
2.2.1.5 Progression of Collapse 2-27
2.2.2 WTC 2 2-27
2.2.2.1 Initial Damage From Aircraft Impact 2-27
2.2.2.2 Preliminary Structural Analysis 2-32
2.2.2.3 Fire Development 2-34
2.2.2.4 Evacuation 2-35
2.2.2.5 Initiation of Collapse 2-35
2.2.2.6 Progression of Collapse 2-35
2.2.3 Substructure 2-35
2.3 Observations and Findings 2-36
2.4 Recommendations 2-39
2.5 References 2-40

3 WTC 3

3.1 Design and Construction Features 3-1
3.1.1 Project Overview 3-1
3.1.2 Building Description 3-1
3.1.3 Structural Description 3-2
3.2 1993 Attack 3-5
3.3 2001 Attacks 3-5
3.3.1 Fire and Evacuation 3-5
3.3.2 Building Response 3-6
3.4 Observations 3-8
3.5 Recommendations 3-8
3.5 References 3-8

4 WTC 4, 5, and 6

4.1 Design and Construction Features 4-1
  4.1.1 Structural Design Features 4-1
  4.1.2 Fire Protection Features 4-2
4.2 Building Loads and Performance 4-4
  4.2.1 Impact Damage to WTC 5 4-7
  4.2.2 Fire Damage 4-9
4.3 Analysis of Building Performance 4-10
  4.3.1 Steel and Frame Behavior 4-10
  4.3.2 WTC 5 – Local Collapse Mechanisms 4-15
4.4 Observations and Findings 4-16
4.5 Recommendations 4-21
4.6 References 4-21

5 WTC 7

5.1 Introduction 5-1
5.2 Structural Description 5-3
  5.2.1 Foundations 5-3
  5.2.2 Structural Framing 5-4
  5.2.3 Transfer Trusses and Girders 5-4
  5.2.4 Connections 5-8
5.3 Fire Protection Systems 5-10
  5.3.1 Egress Systems 5-10
  5.3.2 Detection and Alarm 5-10
  5.3.3 Compartmentalization 5-11
  5.3.4 Suppression Systems 5-12
  5.3.5 Power 5-13
5.4 Building Loads 5-13
5.5 Timeline of Events Affecting WTC 7 on September 11, 2001 5-16
  5.5.1 Collapse of WTC 2 5-16
  5.5.2 Collapse of WTC 1 5-16
  5.5.3 Fires at WTC 7 5-20

5.5.4 Sequence of WTC 7 Collapse 5-23
5.6 Potential Collapse Mechanism 5-24
5.6.1 Probable Collapse Initiation Events 5-24
5.6.2 Probable Collapse Sequence 5-30
5.7 Observations and Findings 5-31
5.8 Recommendations 5-32
5.9 References 5-32

6 Bankers Trust Building

6.1 Introduction 6-1
6.2 Building Description 6-1
6.3 Structural Damage Description 6-4
6.4 Architectural Damage Description 6-6
6.5 Fireproofing 6-10
6.6 Overall Assessment 6-10
6.7 Analysis 6-11
6.7.1 Key Assumptions 6-12
6.7.2 Model Refinement 6-12
6.7.3 Simulation of Nonlinear Behavior 6-13
6.7.4 Connection Details 6-13
6.7.5 Connection Behavior 6-14
6.8 Observations and Findings 6-15
6.9 Recommendations 6-16
6.10 References 6-16

7 Peripheral Buildings

7.1 Introduction 7-1
7.2 World Financial Center 7-4
7.2.1 The Winter Garden 7-4
7.2.2 WFC 3, American Express Building 7-5
7.3 Verizon Building 7-7
7.4 30 West Broadway 7-13

7.5 130 Cedar Street 7-14
7.6 90 West Street 7-15
7.7 45 Park Place 7-17
7.8 One Liberty Plaza 7-17
7.9 Observations and Findings 7-19
7.10 Recommendations 7-19
7.11 References 7-19

8 Observations, Findings, and Recommendations

8.1 Summary of Report Observations, Findings, and Recommendations 8-1
8.2 Chapter Observations, Findings, and Recommendations 8-2
    8.2.1 Chapter 1: Building Codes and Fire Standards 8-2
    8.2.2 Chapter 2: WTC 1 and WTC 2 8-2
        8.2.2.1 Observations and Findings 8-2
        8.2.2.2 Recommendations 8-5
    8.2.3 Chapter 3: WTC 3 8-6
        8.2.3.1 Observations 8-6
        8.2.3.2 Recommendations 8-6
    8.2.4 Chapter 4: WTC 4, 5, and 6 8-6
        8.2.4.1 Observations and Findings 8-6
        8.2.4.2 Recommendations 8-7
    8.2.5 Chapter 5: WTC 7 8-7
        8.2.5.1 Observations and Findings 8-7
        8.2.5.2 Recommendations 8-8
    8.2.6 Chapter 6: Bankers Trust 8-8
        8.2.6.1 Observations and Findings 8-8
        8.2.6.2 Recommendations 8-9
    8.2.7 Chapter 7: Peripheral Buildings 8-10
        8.2.7.1 Observations and Findings 8-10
        8.2.7.2 Recommendations 8-10
    8.2.8 Appendix C: Limited Metallurgical Examination 8-10
        8.2.8.1 Observations and Findings 8-10
        8.2.8.2 Recommendations 8-11
8.3 Building Performance Study Recommendations for Future Study 8-11
    8.3.1 National Response 8-11
    8.3.2 Interaction of Structural Elements and Fire 8-11
    8.3.3 Interaction of Professions in Design 8-12

8.3.4 Fire Protection Engineering Discipline 8-12
8.3.5 Building Evacuation 8-12
8.3.6 Emergency Personnel 8-12
8.3.7 Education of Stakeholders 8-13
8.3.8 Study Process 8-13
8.3.9 Archival Information 8-13
8.3.10 SEAoNY Structural Engineering Emergency Response Plan 8-13

A Overview of Fire Protection in Buildings

A.1 Introduction A-1
A.2 Fire Behavior A-1
A.2.1 Burning Behavior of Materials A-1
A.2.2 Stages of Fire Development A-4
A.2.3 Behavior of Fully Developed Fires A-4
A.3 Structural Response to Fire A-5
A.3.1 Effect of Fire on Steel A-5
A.3.1.1 Introduction A-5
A.3.1.2 Evaluating Fire Resistance A-6
A.3.1.3 Response of High-rise, Steel-frame Buildings in Previous Fire Incidents A-9
A.3.1.4 Properties of Steel A-10
A.3.1.5 Fire Protection Techniques for Steel A-14
A.3.1.6 Temperature Rise in Steel A-14
A.3.1.7 Factors Affecting Performance of Steel Structures in Fire A-17
A.3.2 Effect of Fire on Concrete A-19
A.3.2.1 General A-19
A.3.2.2 Properties of Lightweight Concrete A-19
A.3.3 Fire and Structural Modeling A-22
A.4 Life Safety A-23
A.4.1 Evacuation Process A-24
A.4.2 Analysis A-24
A.5 References A-26

B Structural Steel and Steel Connections

B.1 Structural Steel B-1
B.2 Mechanical Properties B-2

B.3 WTC 1 and WTC 2 Connection Capacity B-4
  B.3.1 Background B-4
  B.3.2 Observations B-5
  B.3.3 Connectors B-5
B.4 Examples of WTC 1 and WTC 2 Connection Capacity B-7
  B.4.1 Bolted Column End Plates B-7
  B.4.2 Bolted Spandrel Connections B-8
  B.4.3 Floor Truss Seated End Connections at Spandrel Beam and Core B-9
  B.4.4 WTC 5 Column-tree Shear Connections B-12
B.5 References B-14

C Limited Metallurgical Examination

C.1 Introduction C-1
C.2 Sample 1 (From WTC 7) C-1
C.3 Summary for Sample 1 .... C-5
C.4 Sample 2 (From WTC 1 or WTC 2) C-5
C.5 Summary for Sample 2 .... C-13
C.6 Suggestions for Future Research C-13

D WTC Steel Data Collection

D.1 Introduction D-1
D.2 Project Background D-1
D.3 Methods D-2
  D.3.1 Identifying and Saving Pieces D-2
  D.3.2 Documenting Pieces D-5
  D.3.3 Getting Coupons D-8
D.4 Data Collected D-10
D.5 Conclusions and Future Work D-13
D.6 References D-13

E Aircraft Information

General Specifications E-1

F Structural Engineers Emergency Response Plan

G Acknowledgments

H Acronyms and Abbreviations

I Metric Conversions

Tables

Table 1.1 Timeline of Major Events 1-10
Table 2.1 Estimated Openings in Exterior Walls of WTC 1 2-23
Table 5.1 WTC 7 Tenants 5-2
Table 5.2 WTC 7 Fuel Distribution Systems 5-14
Table 7.1 DoB/SEAoNY Cooperative Building Damage Assessment – November 7, 2001 7-3
Table A.1 Peak Heat Release Rates of Various Materials (NFPA 92B and NFPA 72) A-3
Table A.2 Fire Duration in Previous Fire Incidents in Steel-frame Buildings A-10
Table A.3 Critical Temperatures for Various Types of Steel A-15
Table A.4 Test Methods for Spray-applied Fireproofing Materials A-18

Figures

Chapter 1

Figure 1-1 WTC site map. 1-3
Figure 1-2 Approximate flight paths of aircraft. 1-5
Figure 1-3 WTC impact locations and resulting fireballs. 1-5
Figure 1-4 Areas of aircraft debris impact. 1-6
Figure 1-5 Fireball erupts on the north face of WTC 2 as United Airlines Flight 175 strikes the building. 1-7
Figure 1-6 View of the north and east faces showing fire and impact damage to both towers. 1-7
Figure 1-7 Schematic depiction of areas of collapse debris impact, based on aerial photographs and documented damage. 1-9
Figure 1-8 Seismic recordings on east-west component at Palisades, NY, for events at WTC on September 11, 2001, distance 34 km. 1-11

Figure 1-9A Satellite photograph of the WTC site taken before the attacks. 1-12

Figure 1-9B Satellite photograph of the WTC site taken after the attacks. 1-13

Figure 1-10 Comparison of high-rise building and aircraft sizes. 1-19

Chapter 2

Figure 2-1 Representative floor plan (based on floor plan for 94th and 95th floors of WTC 1). 2-2

Figure 2-2 Representative structural framing plan, upper floors. 2-4

Figure 2-3 Partial elevation of exterior bearing-wall frame showing exterior wall module construction. 2-6

Figure 2-4 Base of exterior wall frame. 2-7

Figure 2-5 Structural tube frame behavior. 2-7

Figure 2-6 Floor truss member with detail of end connection. 2-8

Figure 2-7 Erection of prefabricated components, forming exterior wall and floor deck units. 2-9

Figure 2-8 Erection of floor framing during original construction. 2-9

Figure 2-9 Cross-section through typical floor trusses, showing transverse truss. 2-9

Figure 2-10 Outrigger truss system at tower roof. 2-10

Figure 2-11 Location of subterranean structure. 2-11

Figure 2-12 Floor plan of 94th and 95th floors of WTC 1 showing egress stairways. 2-14

Figure 2-13 Zone of aircraft impact on the north face of WTC 1. 2-16

Figure 2-14 Approximate zone of impact of aircraft on the north face of WTC 1. 2-17

Figure 2-15 Impact damage to the north face of WTC 1. 2-18

Figure 2-16 Impact damage to exterior columns on the north face of WTC 1. 2-18

Figure 2-17 Approximate debris location on the 91st floor of WTC 1. 2-19

Figure 2-18 Landing gear found at the corner of West and Rector Streets 2-19

Figure 2-19 Redistribution of load after aircraft impact. 2-20

Figure 2-20 Expansion of floor slabs and framing results in outward deflection of columns and potential overload. 2-25

Figure 2-21 Buckling of columns initiated by failure of floor joist connections. 2-26

Figure 2-22 Catenary action of floor joists on several floors initiates column buckling failures. 2-26

Figure 2-23 Aerial photograph of the WTC site after September 11 attack showing adjacent buildings damaged by debris from the collapse of WTC 1. 2-28

Figure 2-24 Southeast corner of WTC 2 shortly after aircraft impact. 2-28
Figure 2-25 Approximate zone of impact of aircraft on the south face of WTC 2. 2-29
Figure 2-26 Impact damage to the south face of WTC 2. 2-30
Figure 2-27 Impact damage to exterior columns on the south face of WTC 2. 2-30
Figure 2-28 Conflagration and debris exiting the north wall of WTC 2, behind WTC 1. 2-31
Figure 2-29 A portion of the fuselage of United Airlines Flight 175 on the roof of WTC 5. 2-32
Figure 2-30 North face of WTC 2 opposite the zone of impact on the south face, behind WTC 1. 2-33
Figure 2-31 Plot of column utilization ratio at the 80th floor of WTC 2, viewed looking outward. 2-34
Figure 2-32 The top portion of WTC 2 falls to the east, then south, as viewed from the northeast. 2-36
Figure 2-33 Damage to substructure slabs caused by collapses of WTC 1 and WTC 2. 2-36

Chapter 3

Figure 3-1 Developed north and west elevations. 3-2
Figure 3-2 Developed south and east elevations. 3-2
Figure 3-3 Typical hotel floor plan. 3-3
Figure 3-4 Typical hotel floor framing plan. 3-4
Figure 3-5 Typical transverse bracing elevation. 3-5
Figure 3-6 Exterior columns from WTC 2 collapse falling on the southern part of WTC 3. 3-6
Figure 3-7 Partial collapse of WTC 3 after collapse of WTC 2. 3-7
Figure 3-8 Remains of WTC 3 after collapse of WTC 1 and WTC 2. 3-8

Chapter 4

Figure 4-1 Typical floor plan for WTC 5. 4-2
Figure 4-2 Typical column-tree system (not to scale). 4-3
Figure 4-3 Typical interior bay framing in WTC 5. 4-3
Figure 4-4 Stairway enclosure core locations in WTC 5. 4-4
Figure 4-5 Damage to WTC 4. 4-5
Figure 4-6 Damage to WTC 5. 4-5
Figure 4-7 Approximate locations of damaged floor areas of WTC 5. 4-6
Figure 4-8 Damage to WTC 6. 4-8
Figure 4-9 Impact damage to WTC 6. 4-8

Figure 4-10 Impact damage to the exterior façade of WTC 6. 4-9

Figure 4-11 WTC 5 façade damage. 4-10

Figure 4-12 Impact damage to WTC 5. 4-11

Figure 4-13 WTC 5 on fire. 4-13

Figure 4-14 Deformed beams in WTC 5. 4-13

Figure 4-15 Unburned bookstore in WTC 5. 4-14

Figure 4-16 Looking through the door into the undamaged stair tower in WTC 5. 4-14

Figure 4-17 Buckled beam flange and column on the 8th floor of WTC 5 that was weakened by fire. 4-15

Figure 4-18 Internal collapsed area in WTC 5. 4-16

Figure 4-19 Internal collapsed area in WTC 5. 4-17

Figure 4-20 Internal collapsed area in WTC 5. 4-18

Figure 4-21 Internal collapsed area in WTC 5 with closeup of connection failure at column tree. 4-18

Figure 4-22 Connection samples. 4-19

Chapter 5

Figure 5-1 Foundation plan – WTC 7. 5-3

Figure 5-2 Plan view of typical floor framing. 5-4

Figure 5-3 Elevations of building and core area. 5-5

Figure 5-4 Fifth floor diaphragm plan showing T-sections imbedded in 14-inch slab. 5-6

Figure 5-5 3-D diagram showing relations of trusses and transfer girders. 5-6

Figure 5-6 Seventh floor plan showing locations of transfer trusses and girders. 5-7

Figure 5-7 Truss 1 detail. 5-8

Figure 5-8 Truss 2 detail. 5-9

Figure 5-9 Truss 3 detail. 5-10

Figure 5-10 Cantilever transfer girder detail. 5-11

Figure 5-11 Compartmentalization provided by concrete floor slabs. 5-12

Figure 5-12 Sequence of debris generated by collapses of WTC 2, 1, and 7. 5-17

Figure 5-13 Pedestrian bridge (bottom center) still standing after WTC 2 has collapsed, sending substantial dust and debris onto the street, but before WTC 1 (top center) has collapsed. 5-18

Figure 5-14 View from the north of the WTC 1 collapse and spread of debris around WTC 7. 5-18

Figure 5-15 Debris from the collapse of WTC 1 located between WTC 7 and the Verizon building. ... 5-19

Figure 5-16 Damage to the southeast corner of WTC 7, looking from West Street. 5-19

Figure 5-17 Building damage to the southwest corner and smoke plume from south face of WTC 7, looking from the World Financial Plaza. 5-20

Figure 5-18 WTC 7, with a large volume of dark smoke rising from it, just visible behind WFC 1 (left). 5-21

Figure 5-19 Fires on the 11th and 12th floors of the east face of WTC 7. 5-22

Figure 5-20 View from the north of WTC 7 with both mechanical penthouses intact. 5-24

Figure 5-21 East mechanical penthouse collapsed. 5-25

Figure 5-22 East and now west mechanical penthouses gone. 5-25

Figure 5-23 View from the north of the "kink" or fault developing in WTC 7. 5-26

Figure 5-24 Areas of potential transfer truss failure. 5-27

Figure 5-25 Debris cloud from collapse of WTC 7. 5-27

Figure 5-26 Debris generated after collapse of WTC 7. 5-28

Chapter 6

Figure 6-1 North face of Bankers Trust building with impact damage between floors 8 and 23. 6-1

Figure 6-2 Closeup of area of partial collapse. 6-2

Figure 6-3 Floor plan above the 2nd level (ground floor extension not shown). 6-3

Figure 6-4 Area of initial impact of debris at the 23rd floor. 6-4

Figure 6-5 Approximate zones of damage – 19th through 22nd floors, 16th through 18th floors, 11th through 15th floors, and 9th through 10th floors. 6-5

Figure 6-6 Moment-connected beams to columns. 6-7

Figure 6-7 Column with the remains of two moment connections. 6-7

Figure 6-8 Failed shear connection of beam web to column web. 6-8

Figure 6-9 Suspended column D-8 at the 15th floor. 6-8

Figure 6-10 Area of collapsed floor slab in bays between C-8, E-8, C-7, and E-7, from 15th floor. 6-9

Figure 6-11 Bankers Trust lobby (note debris has been swept into piles). 6-9

Figure 6-12 Office at north side of the 8th floor. 6-10

Figure 6-13 3-D ANSYS model of flange and shear plate moment connection. 6-14

Figure 6-14 3-D ANSYS model of flange and seat moment connection. 6-14

Chapter 7

Figure 7-1 New York City DDC/DoB Cooperative Building Damage Assessment Map of November 7, 2001 (based on SEAoNY inspections). 7-2
Figure 7-2 Southeast corner of WFC 3. 7-5
Figure 7-3 View of Winter Garden damage from West Street, with WTC 1 debris in front of WFC 2. 7-6
Figure 7-4 View of Winter Garden damage from West Street, with WTC 1 debris leaning against WFC 3. 7-6
Figure 7-5 Interior damage at floor 20 of WFC 3. 7-7
Figure 7-6 Verizon building – damage to east elevation (Washington Street). 7-8
Figure 7-7 Verizon building – damage to east elevation (Washington Street) due to WTC 7 framing leaning against the building. 7-9
Figure 7-8 Verizon building – damage to east elevation (Washington Street). 7-9
Figure 7-9 Verizon building – column damage on east elevation (Washington Street). 7-10
Figure 7-10 Verizon building – damage to south elevation (Vesey Street). 7-11
Figure 7-11 Verizon building – localized damage to south elevation (Vesey Street). 7-11
Figure 7-12 Verizon building – detail of damage to south elevation (Vesey Street). 7-12
Figure 7-13 30 West Broadway – south façade, 6th floor to roof, looking northeast. 7-13
Figure 7-14 130 Cedar Street and 90 West Street. 7-14
Figure 7-15 Interior of 90 West Street showing typical construction features. 7-16
Figure 7-16 Buckling damage at top of column on floor 8 of 90 West Street. 7-17
Figure 7-17 Buckling damage at top of column on floor 23 of 90 West Street. 7-18
Figure 7-18 One Liberty Plaza – south elevation, lower floors. 7-19
Figure 7-19 One Liberty Plaza – south elevation, upper floors. 7-20

Appendix A

Figure A-1 Heat release rate for office module. A-2
Figure A-2 Fire growth rates (the SFPE Handbook of Fire Protection Engineering). A-3
Figure A-3 Comparison of exposure temperatures in standard tests. A-6
Figure A-4 Thermal properties of steel at elevated temperatures. A-11
Figure A-5 Stress-strain curves for structural steel (ASTM A36) at a range of temperatures. A-11
Figure A-6 Strength of steel at elevated temperatures. A-12

Figure A-7 Modulus of elasticity at elevated temperatures for structural steels and steel reinforcing bars. A-13

Figure A-8 Reduction of the yield strength of cold-formed light-gauge steel at elevated temperatures. A-13

Figure A-9 Steel temperature rise due to fire exposure for unprotected steel column. A-16

Figure A-10 Steel temperature rise due to fire exposure for steel column protected with 1 inch of spray-applied fireproofing. A-16

Figure A-11 The effect of temperature on the modulus of elasticity strength of different types of concretes (Kodur and Harmathy 2002) A-20

Figure A-12 Reduction of the compressive strength of two lightweight concretes (one with natural sand) at elevated temperatures (Kodur and Harmathy 2002). A-21

Figure A-13 Usual ranges of variation for the volume-specific heat of normal-weight and lightweight concretes (Kodur and Harmathy 2002). A-21

Figure A-14 Specific flow rate as a function of density (SPFE Handbook of Fire Protection Engineering). A-25

Figure A-15 Estimated evacuation times for high-rise buildings. A-26

Appendix B

Figure B-1 Exterior column end plates. B-1

Figure B-2 Tensile stress-strain curves for three ASTM-designation steels (Brockenbrough and Johnston 1968, Tall 1974). B-3

Figure B-3 Expanded yield portion of the tensile stress-strain curves (Tall 1974). B-3

Figure B-4 Effect of high strain rate on shape of stress-strain diagram (Tall 1974). B-4

Figure B-5 Column tree showing bolt bearing shear failures of spandrel connection. B-6

Figure B-6 Shear fracture failure of fillet welds connecting a W-shape column to a box core column. B-7

Figure B-7 Bent and fractured bolts at a column four-bolt connection. B-8

Figure B-8 Typical truss top chord connections to column/spandrel beam and to the core beam. B-10

Figure B-9 (A) Visco-elastic damper angles bolted to angle welded to spandrel plate and (B) failed bearing seat connection B-11

Figure B-10 (A) Bracket plate welded to the column/spandrel plate and (B) horizontal plate brace with shear connectors welded to the failed bracket. B-11

Figure B-11 Shear failure of floor joist connections from column/spandrel plate. B-12

Appendix C

Figure C-1 Eroded A36 wide-flange beam. C-1
Figure C-2 Closeup view of eroded wide-flange beam section. C-2
Figure C-3 Mounted and polished severely thinned section removed from the wide-flange beam shown in Figure C-1. .... C-2
Figure C-4 Optical microstructure near the steel surface. C-3
Figure C-5 Another hot corrosion region near the steel surface (etched with 4 percent nital). C-3
Figure C-6 Microstructure of A36 steel. C-4
Figure C-7 Deep penetration of liquid into the steel. C-4
Figure C-8 Qualitative chemical analysis. C-5
Figure C-9 Qualitative chemical analysis. C-6
Figure C-10 Grain boundary corrosion attack. C-6
Figure C-11 Microstructure of a typical region showing the surface and grain boundary corrosion attack of Sample 2. .... C-7
Figure C-12 Higher magnification of the region shown in Figure C-10. .... C-7
Figure C-13 Regions where chemical analysis was performed. C-8
Figure C-14 Gradient of sulfides into the steel from the oxide-metal interface. C-12

Appendix D

Figure D-1 Mixed, unsorted steel upon delivery to salvage yard. D-2
Figure D-2 Torch cutting of very large pieces into more manageable pieces of a few tons each. D-3
Figure D-3 Pile of unsorted mixed steel, with sorted, large steel pieces being lifted and cut into smaller pieces. D-3
Figure D-4 Engineer climbing in unprocessed steel pile to inspect and mark promising pieces D-4
Figure D-5 Stenciled markings on WTC 2 perimeter column from floors 68-71. .... D-5
Figure D-6 Steel pieces marked "SAVE." D-6
Figure D-7 Engineers measuring and recording steel piece dimensions. D-6
Figure D-8 Engineer measuring spandrel plate thickness (t_s). D-7
Figure D-9 Measurement of 1/4 inch for web thickness (t_w). D-7
Figure D-10 Measured dimensions of the steel pieces. D-8
Figure D-11 Burnt steel piece marked for cutting of coupon. D-9
Figure D-12 Coupon cut from WTC 5 showing web tear-out at bolts. D-9
Figure D-13 WTC 1 or WTC 2 core column (C-74). D-10

Figure D-14 WTC 7 W14 column tree with beams attached to two floors. D-11
Figure D-15 Built-up member with failure along stitch welding. D-11
Figure D-16 Engineer inspecting fire damage of perimeter column tree from WTC 1 or WTC 2. .... D-12
Figure D-17 Seat-connected in fire-damaged W14 column from WTC 7. .... D-12
Figure D-18 WTC 1 or WTC 2 floor-truss section with seat connection fractured along welds. D-13

Executive Summary

Following the September 11, 2001, attacks on New York City's World Trade Center (WTC), the Federal Emergency Management Agency (FEMA) and the Structural Engineering Institute of the American Society of Civil Engineers (SEI/ASCE), in association with New York City and several other Federal agencies and professional organizations, deployed a team of civil, structural, and fire protection engineers to study the performance of buildings at the WTC site.

The events following the attacks in New York City were among the worst building disasters in history and resulted in the largest loss of life from any single building collapse in the United States. Of the 58,000 people estimated to be at the WTC Complex, over 3,000 lost their lives that day, including 343 emergency responders. Two commercial airliners were hijacked, and each was flown into one of the two 110-story towers. The structural damage sustained by each tower from the impact, combined with the ensuing fires, resulted in the total collapse of each building. As the towers collapsed, massive debris clouds consisting of crushed and broken building components fell onto and blew into surrounding structures, causing extensive collateral damage and, in some cases, igniting fires and causing additional collapses. In total, 10 major buildings experienced partial or total collapse and approximately 30 million square feet of commercial office space was removed from service, of which 12 million belonged to the WTC Complex.

The purpose of this study was to examine the damage caused by these events, collect data, develop an understanding of the response of each affected building, identify the causes of observed behavior, and identify studies that should be performed. The immediate effects of the aircraft impacts on each tower, the spread of fires following the crashes, the fire-induced reduction of structural strength, and the mechanism that led to the collapse of each tower were studied. Additionally, the performance of buildings in the immediate vicinity of the towers was studied to determine the effects of damage from falling debris and fires. Recommendations are presented for more detailed engineering studies, to complete the assessments and produce improved guidance and tools for building design and performance evaluation.

As each tower was struck, extensive structural damage, including localized collapse, occurred at the several floor levels directly impacted by the aircraft. Despite this massive localized damage, each structure remained standing. However, as each aircraft impacted a building, jet fuel on board ignited. Part of this fuel immediately burned off in the large fireballs that erupted at the impact floors. Remaining fuel flowed across the floors and down elevator and utility shafts, igniting intense fires throughout upper portions of the buildings. As these fires spread, they further weakened the steel-framed structures, eventually leading to total collapse.

The collapse of the twin towers astonished most observers, including knowledgeable structural engineers, and, in the immediate aftermath, a wide range of explanations were offered in an attempt to help the public understand these tragic events. However, the collapse of these symbolic buildings entailed a complex series of events that were not identical for each tower. To determine the sequence of events, likely root causes, and methods or technologies that may improve or mitigate the building performance observed, FEMA and ASCE formed a Building Performance Study (BPS) Team consisting of specialists in tall building design, steel and connection technology, fire and blast engineering, and structural investigation and analysis.

The Team conducted field observations at the WTC site and steel salvage yards, removed and tested samples of the collapsed structures, viewed hundreds of hours of video and thousands of still photographs, conducted interviews with witnesses and persons involved in the design, construction, and maintenance of each of the affected buildings, reviewed construction documents, and conducted preliminary analyses of the damage to the WTC towers.

With the information and time available, the sequence of events leading to the collapse of each tower could not be definitively determined. However, the following observations and findings were made:

> The structural damage sustained by each of the two buildings as a result of the terrorist attacks was massive. The fact that the structures were able to sustain this level of damage and remain standing for an extended period of time is remarkable and is the reason that most building occupants were able to evacuate safely. Events of this type, resulting in such substantial damage, are generally not considered in building design, and the ability of these structures to successfully withstand such damage is noteworthy.
>
> Preliminary analyses of the damaged structures, together with the fact the structures remained standing for an extended period of time, suggest that, absent other severe loading events such as a windstorm or earthquake, the buildings could have remained standing in their damaged states until subjected to some significant additional load. However, the structures were subjected to a second, simultaneous severe loading event in the form of the fires caused by the aircraft impacts.
>
> The large quantity of jet fuel carried by each aircraft ignited upon impact into each building. A significant portion of this fuel was consumed immediately in the ensuing fireballs. The remaining fuel is believed either to have flowed down through the buildings or to have burned off within a few minutes of the aircraft impact. The heat produced by this burning jet fuel does not by itself appear to have been sufficient to initiate the structural collapses. However, as the burning jet fuel spread across several floors of the buildings, it ignited much of the buildings' contents, causing simultaneous fires across several floors of both buildings. The heat output from these fires is estimated to have been comparable to the power produced by a large commercial power generating station. Over a period of many minutes, this heat induced additional stresses into the damaged structural frames while simultaneously softening and weakening these frames. This additional loading and the resulting damage were sufficient to induce the collapse of both structures.
>
> The ability of the two towers to withstand aircraft impacts without immediate collapse was a direct function of their design and construction characteristics, as was the vulnerability of the two towers to collapse a result of the combined effects of the impacts and ensuing fires. Many buildings with other design and construction characteristics would have been more vulnerable to collapse in these events than the two towers, and few may have been less vulnerable. It was not the purpose of this study to assess the code-conformance of the building design and construction, or to judge the adequacy of these features. However, during the course of this study, the structural and fire protection features of the buildings were examined. The study did not reveal any specific structural features that would be regarded as substandard, and, in fact, many structural and fire protection features of the design and construction were found to be superior to the minimum code requirements.

Several building design features have been identified as key to the buildings' ability to remain standing as long as they did and to allow the evacuation of most building occupants. These included the following:

- robustness and redundancy of the steel framing system
- adequate egress stairways that were well marked and lighted
- conscientious implementation of emergency exiting training programs for building tenants

Similarly, several design features have been identified that may have played a role in allowing the buildings to collapse in the manner that they did and in the inability of victims at and above the impact floors to safely exit. These features should not be regarded either as design deficiencies or as features that should be prohibited in future building codes. Rather, these are features that should be subjected to more detailed evaluation, in order to understand their contribution to the performance of these buildings and how they may perform in other buildings. These include the following:

- the type of steel floor truss system present in these buildings and their structural robustness and redundancy when compared to other structural systems
- use of impact-resistant enclosures around egress paths
- resistance of passive fire protection to blasts and impacts in buildings designed to provide resistance to such hazards
- grouping emergency egress stairways in the central building core, as opposed to dispersing them throughout the structure

During the course of this study, the question of whether building codes should be changed in some way to make future buildings more resistant to such attacks was frequently explored. Depending on the size of the aircraft, it may not be technically feasible to develop design provisions that would enable all structures to be designed and constructed to resist the effects of impacts by rapidly moving aircraft, and the ensuing fires, without collapse. In addition, the cost of constructing such structures might be so large as to make this type of design intent practically infeasible.

Although the attacks on the World Trade Center are a reason to question design philosophies, the BPS Team believes there are insufficient data to determine whether there is a reasonable threat of attacks on specific buildings to recommend inclusion of such requirements in building codes. Some believe the likelihood of such attacks on any specific building is deemed sufficiently low to not be considered at all. However, individual building developers may wish to consider design provisions for improving redundancy and robustness for such unforeseen events, particularly for structures that, by nature of their design or occupancy, may be especially susceptible to such incidents. Although some conceptual changes to the building codes that could make buildings more resistant to fire or impact damage or more conducive to occupant egress were identified in the course of this study, the BPS Team felt that extensive technical, policy, and economic study of these concepts should be performed before any specific code change recommendations are developed. This report specifically recommends such additional studies. Future building code revisions may be considered after the technical details of the collapses and other building responses to damage are better understood.

Several other buildings, including the Marriott Hotel (WTC 3), the South Plaza building (WTC 4), the U.S. Customs building (WTC 6), and the Winter Garden, experienced severe damage as a result of the massive quantities of debris that fell on them when the two towers collapsed. The St. Nicholas Greek Orthodox Church just south of WTC 2 was completely destroyed by the debris that fell on it.

WTC 5, WTC 7, 90 West Street, the Bankers Trust building, the Verizon building, and World Financial Center 3 were impacted by large debris from the collapsing twin towers and suffered structural damage, but arrested collapse to localized areas. The performance of these buildings demonstrates the inherent ability of redundant steel-framed structures to withstand extensive damage from earthquakes, blasts, and other extreme events without progressive collapse.

The debris from the collapses of the WTC towers also initiated fires in surrounding buildings, including WTC 4, 5, 6, and 7; 90 West Street; and 130 Cedar Street. Many of the buildings suffered severe fire damage but remained standing. However, two steel-framed structures experienced fire-induced collapse. WTC 7 collapsed completely after burning unchecked for approximately 7 hours, and a partial collapse occurred in an interior section of WTC 5. Studies of WTC 7 indicate that the collapse began in the lower stories, either through failure of major load transfer members located above an electrical substation structure or in columns in the stories above the transfer structure. The collapse of WTC 7 caused damage to the Verizon building and 30 West Broadway. The partial collapse of WTC 5 was not initiated by debris and is possibly a result of fire-induced connection failures. The collapse of these structures is particularly significant in that, prior to these events, no protected steel-frame structure, the most common form of large commercial construction in the United States, had ever experienced a fire-induced collapse. Thus, these events may highlight new building vulnerabilities, not previously believed to exist.

In the study of the WTC towers and the surrounding buildings that were subsequently damaged by falling debris and fire, several issues were found to be critical to the observed building performance in one or more buildings.

These issues fall into several broad topics that should be considered for buildings that are being evaluated or designed for extreme events. It may be that some of these issues should be considered for all buildings; however, additional studies are required before general recommendations, if any, can be made for all buildings. The issues identified from this study of damaged buildings in or near the WTC site have been summarized into the following points:

a. Structural framing systems need redundancy and/or robustness, so that alternative paths or additional capacity are available for transmitting loads when building damage occurs.

b. Fireproofing needs to adhere under impact and fire conditions that deform steel members, so that the coatings remain on the steel and provide the intended protection.

c. Connection performance under impact loads and during fire loads needs to be analytically understood and quantified for improved design capabilities and performance as critical components in structural frames.

d. Fire protection ratings that include the use of sprinklers in buildings require a reliable and redundant water supply. If the water supply is interrupted, the assumed fire protection is greatly reduced.

e. Egress systems currently in use should be evaluated for redundancy and robustness in providing egress when building damage occurs, including the issues of transfer floors, stair spacing and locations, and stairwell enclosure impact resistance.

f. Fire protection ratings and safety factors for structural transfer systems should be evaluated for their adequacy relative to the role of transfer systems in building stability.

The BPS Team has developed recommendations for specific issues, based on the study of the performance of the WTC towers and surrounding buildings in response to the impact and fire damage that occurred. These recommendations have a broader scope than the important issue of building concepts and design for mitigating damage from terrorist attacks, and also address the level at which resources should be expended for aircraft security, how the fire protection and structural engineering communities should increase their interaction in building design and construction, possible considerations for improved egress in damaged structures, the public understanding of typical building design capacities, issues related to the study process and future activities, and issues for communities to consider when they are developing emergency response plans that include engineering response.

National Response. Resources should be directed primarily to aviation and other security measures rather than to hardening buildings against airplane impact. The relationship and cooperation between public and private organizations should be evaluated to determine the most effective mechanisms and approaches in the response of the nation to such disasters.

Interaction of Structural Elements and Fire. The existing prescriptive fire resistance rating method (ASTM E119) does not provide sufficient information to determine how long a building component in a structural system can be expected to perform in an actual fire. A method of assessing performance of structural members and connections as part of a structural system in building fires is needed for designers and emergency personnel.

The behavior of the structural system under fire conditions should be considered as an integral part of the structural design. Recommendations are to:

- Develop design tools, including an integrated model that predicts heating conditions produced by the fire, temperature rise of the structural component, and structural response.
- Provide interdisciplinary training in structures and fire protection for both structural engineers and fire protection engineers.

Performance criteria and test methods for fireproofing materials relative to their durability, adhesion, and cohesion when exposed to abrasion, shock, vibration, rapid temperature rise, and high-temperature exposures need further study.

Interaction of Professions in Design. The structural, fire protection, mechanical, architectural, blast, explosion, earthquake, and wind engineering communities need to work together to develop guidance for vulnerability assessment, retrofit, and the design of concrete and steel structures to mitigate or reduce the probability of progressive collapse under single- and multiple-hazard scenarios.

An improved level of interaction between structural and fire protection engineers is encouraged. Recommendations are to:

- Consider behavior of the structural system under fire as an integral part of the design process.
- Provide cross-training of fire protection and structural engineers in the performance of structures and building fires.

Fire Protection Engineering Discipline. The continued development of a system for performance-based design is encouraged. Recommendations are to:

- Improve the existing models that simulate fire and spread in structures, as well as the impact of fire and smoke on structures and people.
- Improve the database on material burning behavior.

Building Evacuation. The following topics were not explicitly examined during this study, but are recognized as important aspects of designing buildings for impact and fire events. Recommendations for further study are to:

- Perform an analysis of occupant behavior during evacuation of the buildings at WTC to improve the design of fire alarm and egress systems in high-rise buildings.

- Perform an analysis of the design basis of evacuation systems in high-rise buildings to assess the adequacy of the current design practice, which relies on phased evacuation.
- Evaluate the use of elevators as part of the means of egress for mobility-impaired people as well as the general building population for the evacuation of high-rise buildings. In addition, the use of elevators for access by emergency personnel needs to be evaluated.

Emergency Personnel. One of the most serious dangers firefighters and other emergency responders face is partial or total collapse of buildings. Recommended steps to provide better protection to emergency personnel are to:

- Have fire protection and structural engineers assist emergency personnel in developing pre-plans for buildings and structures to include more detailed assessments of hazards and response of structural elements and performance of buildings during fires, including identification of critical structural elements.
- Develop training materials and courses for emergency personnel concerning the effects of fire on steel.
- Review collaboration efforts between the emergency personnel and engineering professions so that engineers may assist emergency personnel in assessments during an incident.

Education of Stakeholders. Stakeholders (e.g., owners, operators, tenants, authorities, designers) should be further educated about building codes, the minimum design loads typically addressed for building design, and the extreme events that are not addressed by building codes. Should stakeholders desire to address events not included in the building codes, they should understand the process of developing and implementing strategies to mitigate damage from extreme events.

Stakeholders should also be educated about the expected performance of their building when renovations, or changes in use or occupancy, occur and the building is subjected to different floor or fire loads. For instance, if the occupancy in a building changes to one with a higher fire hazard, stakeholders should have the fire protection systems reviewed to ensure there is adequate fire protection. Or, if the structural load is increased with a new occupancy, the structural support system should be reviewed to ensure it can carry the new load.

Study Process. This report benefited from a tremendous amount of professional volunteerism in response to this unprecedented national disaster. Improvements can be made that would aid the process for any future efforts. Recommendations are to:

- Provide resources that are proportional to the required level of effort.
- Provide better access to data, including building information, interviews, samples, site photos, and documentation.

Archival Information. Archival information has been collected and provides the groundwork for continued study. It is recommended that a coordinated effort for the preservation of this and other relevant information be undertaken by a responsible organization or agency, capable of maintaining and managing such information. This effort would include:

- cataloging all photographic data collected to date
- enhancing video data collected for both quality and timeline
- conducting interviews with building occupants, witnesses, rescue workers, and any others who may provide valuable information
- initiating public requests for information

SEAoNY Structural Engineering Emergency Response Plan. As with any first-time event, difficulties were encountered at the beginning of the relationship between the volunteer engineering community and the local government agencies. Lessons learned in hindsight can be valuable to other engineering and professional organizations throughout the country. Appendix F presents recommendations that can be used as a basis for the development of other, similar plans.

Therese McAllister
Jonathan Barnett
John Gross
Ronald Hamburger
Jon Magnusson

1 *Introduction*

1.1 Purpose and Scope of Study

The events in New York City (NYC) on September 11, 2001, were among the worst building disasters and loss of life from any single building event in the United States. Over 3,000 people lost their lives that day at the World Trade Center (WTC) site, including 343 emergency responders. The nation was shocked by the attacks and resulting collapse of office buildings that had been in use every day.

This report presents observations, findings, and recommendations regarding the performance of buildings affected by the September 11 attacks on the WTC towers in New York City. This report also describes the structural and fire protection features of the affected buildings and their performance in response to the terrorist attacks. Due to the unprecedented nature, magnitude, and visibility of the terrorist attacks, this event is among the most well-documented in the media, particularly in terms of photographic images, lives affected, and the immediate responses and ensuing sequence of events. An understanding of these events must include the performance of the buildings under extreme conditions beyond building code requirements. This includes determining the probable causes of collapse and identifying lessons to be learned. Recommendations are presented for more detailed engineering studies, to complete the assessments and to produce improved guidance for building design and performance evaluation tools.

During the September 11 attacks, a large number of buildings were extensively damaged by impact and fire events. To study the response of the affected buildings, a diverse group of experts in tall building design, steel structure behavior, fire protection engineering, blast effects, and structural investigations was empaneled into a Building Performance Study (BPS) Team. The study was sponsored by the Federal Emergency Management Agency (FEMA) and the Structural Engineering Institute of the American Society of Civil Engineers (SEI/ASCE). In conducting the study, the BPS Team received tremendous cooperation from the State of New York, the New York City Department of Design and Construction (DDC), the New York City Office of Emergency Management (OEM), the Port Authority of New York and New Jersey (hereafter referred to as the Port Authority), the National Institute of Standards and Technology (NIST), and the Structural Engineers Association of New York (SEAoNY). In addition, the BPS Team was supported by a coalition of organizations that included the American Concrete Institute (ACI), the American Institute of Steel Construction (AISC), the Council of American Structural Engineers (CASE), the International Code Council (ICC), the Council on Tall Buildings and Urban Habitat (CTBUH), the National Council of Structural Engineers Associations (NCSEA), the National Fire Protection Association (NFPA), the Society of Fire Protection Engineers (SFPE), and the Masonry Society (TMS).

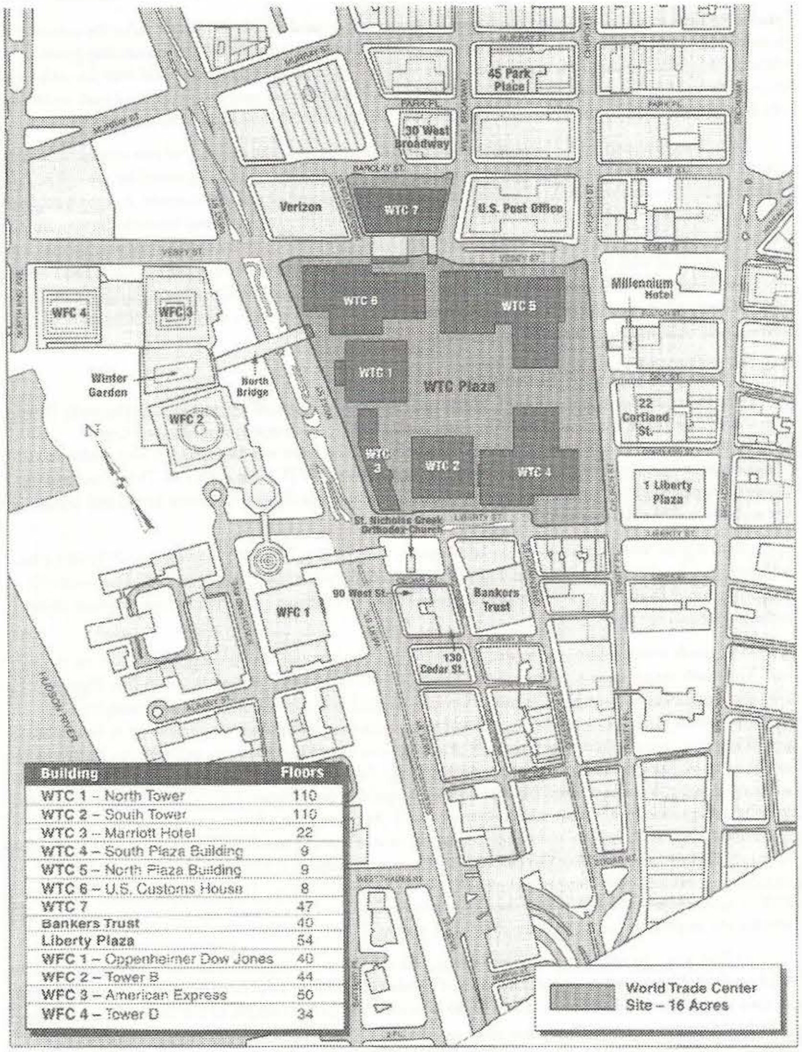
FEMA and ASCE began discussing site studies and teams on September 12, as engineers and emergency management agencies all over the nation rallied to provide support. A number of the team members were at the site immediately after the attacks to assist as needed. As soon as the rescue operations were halted and the FEMA Urban Search and Rescue teams left the site, the BPS Team mobilized to the WTC site and conducted field observations during the week of October 7, 2001. While in New York, the team inspected and photographed the site and individual building conditions, visited the salvage yards receiving steel from the collapsed buildings, attended presentations by design professionals associated with WTC buildings, and reviewed available building drawings. Upon completion of the site visit, the team members continued to collect extensive information and data, including photographs, video footage, and emergency response radio communications; continued surveillance of steel delivered to the recycling yards with the support of SEAoNY volunteers; and conducted additional interviews with direct witnesses of the events as well as participants in the original building design, construction, and maintenance. This information led to the development of a timeline of building loading events and allowed an initial engineering assessment of building performance. The study focus was to determine probable failure mechanisms and to identify areas of future investigation that could lead to practical measures for improving the damage resistance of buildings against such unforeseen events.

1.2 WTC Site

The World Trade Center and adjacent affected buildings were located on New York City's lower west side, adjacent to the Hudson River at the southern tip of Manhattan. As shown in Figure 1-1, the WTC site itself comprises 16 acres with buildings grouped around a 5-acre plaza. It is bounded by Vesey Street to the north, Church Street to the east, Liberty Street to the south, and West Street to the west. The WTC Complex consisted of seven buildings (referred to in this report as WTC 1 through WTC 7), the Port Authority Trans-Hudson (PATH) and Metropolitan Transit Authority (MTA) WTC stations, and associated Concourse areas. The WTC Plaza and its six buildings were originally developed by the Port Authority. Groundbreaking for construction was on August 5, 1966. Steel erection began in August 1968. First tenant occupancy of the 110-story north tower (WTC 1) was in December 1970, and occupancy of the 110-story south tower (WTC 2) began in January 1972. The other WTC buildings were constructed during the 1970s and into the 1980s, with WTC 7 constructed just north of the WTC site in 1985. WTC 3, located immediately west of the south tower, was a 22-story hotel operated by the Marriott Corporation. WTC 4 and 5 were nine-story office buildings, and WTC 6 was an eight-story office building. WTC 7 was a 47-story office building. The seven-building complex provided approximately 12 million square feet of rentable floor space occupied by a variety of government and commercial tenants. Many of the commercial tenants were in the insurance and financial industries. At the time of the September 11 attacks, the entire project had been transferred to a private party under a 99-year capital lease.

The New York Stock Exchange and the Wall Street financial district are located about three blocks southeast of the site. The World Financial Center (WFC) complex was constructed in the early 1980s and is located directly to the west, across West Street. Other prominent buildings immediately surrounding the WTC site include a historic Cass Gilbert designed building at 90 West Street and the Bankers Trust building at 130 Liberty Street, both located immediately to the south; the 1 Liberty Plaza building, located to the east; and the Verizon building, located directly to the north.

A six-story subterranean structure was underneath a large portion of the main WTC Plaza and WTC 1, 2, 3, and 6. Material excavated to construct this site was used to fill a portion of the Hudson River shoreline just across West Street and to create the adjacent World Financial Center (WFC) site. Construction of this deep substructure was a significant challenge, given the proximity of the Hudson River and the presence of a number of tall buildings along the south, east, and north sides of the site. In order to aid the excavation, slurry wall technology was utilized. In this technology, a trench is dug in the eventual location of the perimeter retaining walls. A bentonite slurry is pumped into the trench as it is excavated, and used to keep the trench open against the surrounding earth. Reinforcing steel is lowered into the trench, and concrete is


Murray St.
Park Pl.
45 Park Place
30 West Broadway
Barclay St.
Verizon
WTC 7
U.S. Post Office
Vesey St.
Millennium Hotel
WFC 4
WFC 3
WTC 6
WTC 5
Winter Garden
North Bridge
WTC 1
WTC Plaza
WFC 2
N
22 Cortland St.
WTC 3
WTC 2
WTC 4
1 Liberty Plaza
St. Nicholas Greek Orthodox Church
Liberty St.
90 West St.
Bankers Trust
WFC 1
130 Cedar St.
Hudson River
World Trade Center Site – 16 Acres

Building	Floors
WTC 1 – North Tower	110
WTC 2 – South Tower	110
WTC 3 – Marriott Hotel	22
WTC 4 – South Plaza Building	9
WTC 5 – North Plaza Building	9
WTC 6 – U.S. Customs House	8
WTC 7	47
Bankers Trust	40
Liberty Plaza	54
WFC 1 – Oppenheimer Dow Jones	40
WFC 2 – Tower B	44
WFC 3 – American Express	50
WFC 4 – Tower D	34

Figure 1-1 WTC site map.

placed through a tremie to create a reinforced concrete wall around the site perimeter. After the concrete wall is cured, excavation of the substructure begins. As the excavation progresses below surrounding grade, tiebacks are drilled through the exposed concrete wall and through the surrounding soil into the rock below to provide stability for the excavation. At the WTC site, these tiebacks were temporary and were replaced in the final construction by the subterranean floor slabs that provided lateral support to the walls.

A further challenge to the construction of the substructure was the presence of two existing subway lines across the site. The Interboro Rapid Transit System 1 and 9 subway lines, operated by the MTA, ran north to south across the middle of the site adjacent to the east wall of the substructure. A second subway system, PATH, operated by the Port Authority, made a 180-degree terminal bend beneath the western half of the site. This subway tunnel was temporarily supported across the excavation and incorporated into the final construction with a station provided for this line inside the slurry wall, just west of the 1 and 9 subway lines, and below the Plaza area just east of WTC 1 and partially below WTC 6. Although significant damage was sustained by the buildings, subterranean structure, and subway system, only the performances of the above-grade buildings were assessed in this study.

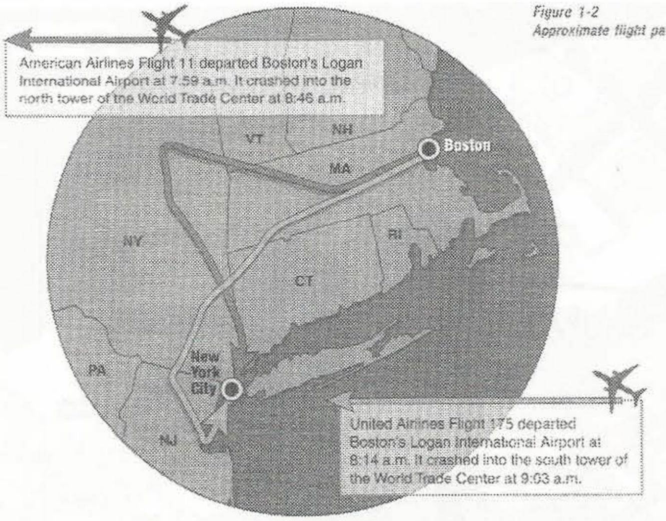
1.3 Timeline and Event Summary

On the morning of September 11, 2001, two hijacked commercial jetliners were deliberately flown into the WTC towers. The first plane, American Airlines Flight 11, originated at Boston's Logan International Airport at 7:59 a.m., Eastern Daylight Time. The plane was flown south, over midtown Manhattan, and crashed into the north face of the north tower (WTC 1) at 8:46 a.m. The second plane, United Airlines Flight 175, departed Boston at 8:14 a.m., and was flown over Staten Island and crashed into the south face of the south tower (WTC 2) at 9:03 a.m.

Both flights, scheduled to arrive in Los Angeles, were Boeing 767-200ER series aircraft loaded with sufficient fuel for the transcontinental flights. These aircraft are described in Appendix E. There were 92 people on board Flight 11 and 65 people on board Flight 175. Figure 1-2 shows the approximate flight paths for the two aircraft.

The north tower was struck between floors 94 and 98, with the impact roughly centered on the north face. The south tower was hit between floors 78 and 84 toward the east side of the south face (Figures 1-3 and 1-4). Each plane banked steeply as it was flown into the building, causing damage across multiple floors. According to Government sources, the speed of impact into the north tower was estimated to be 410 knots, or 470 miles per hour (mph), and the speed of impact into the south tower was estimated to be 510 knots, or 590 mph. As the two aircraft impacted the buildings, fireballs erupted (Figure 1-5) and jet fuel spread across the impact floors and down interior shaftways, igniting fires (Figure 1-6). The term fireball is used to describe deflagration, or ignition, of a fuel vapor cloud. As the resulting fires raged throughout the upper floors of the two WTC towers, thousands attempted to evacuate the buildings. It was estimated by the Port Authority that the population of the WTC complex on September 11, 2001, was 58,000 people. This estimate includes the PATH and MTA stations and the Concourse areas. Almost everyone in WTC 1 and WTC 2 who was below the impact areas was able to safely evacuate the buildings, due to the length of time between the impact and collapse of the individual towers.

At 9:59 a.m., 56 minutes after it was struck, the south tower collapsed. The north tower continued to stand until 10:29 a.m., when it, too, collapsed. The north tower had survived 1 hour and 43 minutes from the time the jetliner crashed into it. Over 3,000 lives were lost in the collapse of the twin towers, counting 2,830 building occupants, 157 airplane crew and passengers, and 343 firefighters, police personnel, and other emergency responders.


VT
NH
MA
Boston
NY
RI
CT
PA
New York City
NJ

American Airlines Flight 11 departed Boston's Logan International Airport at 7:59 a.m. It crashed into the north tower of the World Trade Center at 8:46 a.m.

United Airlines Flight 175 departed Boston's Logan International Airport at 8:14 a.m. It crashed into the south tower of the World Trade Center at 9:03 a.m.

Figure 1-2
Approximate flight paths of aircraft.

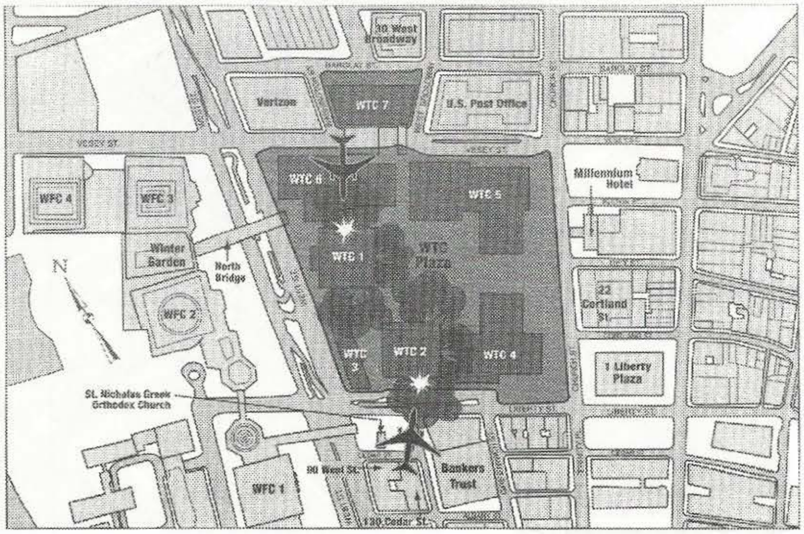

30 West Broadway
Barclay St.
Verizon
WTC 7
U.S. Post Office
Vesey St.
WFC 4
WFC 3
WTC 6
WTC 5
Millennium Hotel
Winter Garden
North Bridge
WTC 1
WTC Plaza
N
WFC 2
22 Cortland St.
WTC 3
WTC 2
WTC 4
1 Liberty Plaza
St. Nicholas Greek Orthodox Church
90 West St.
Bankers Trust
WFC 1
130 Cedar St.
Church St.
Liberty St.

Figure 1-3 WTC impact locations and resulting fireballs.

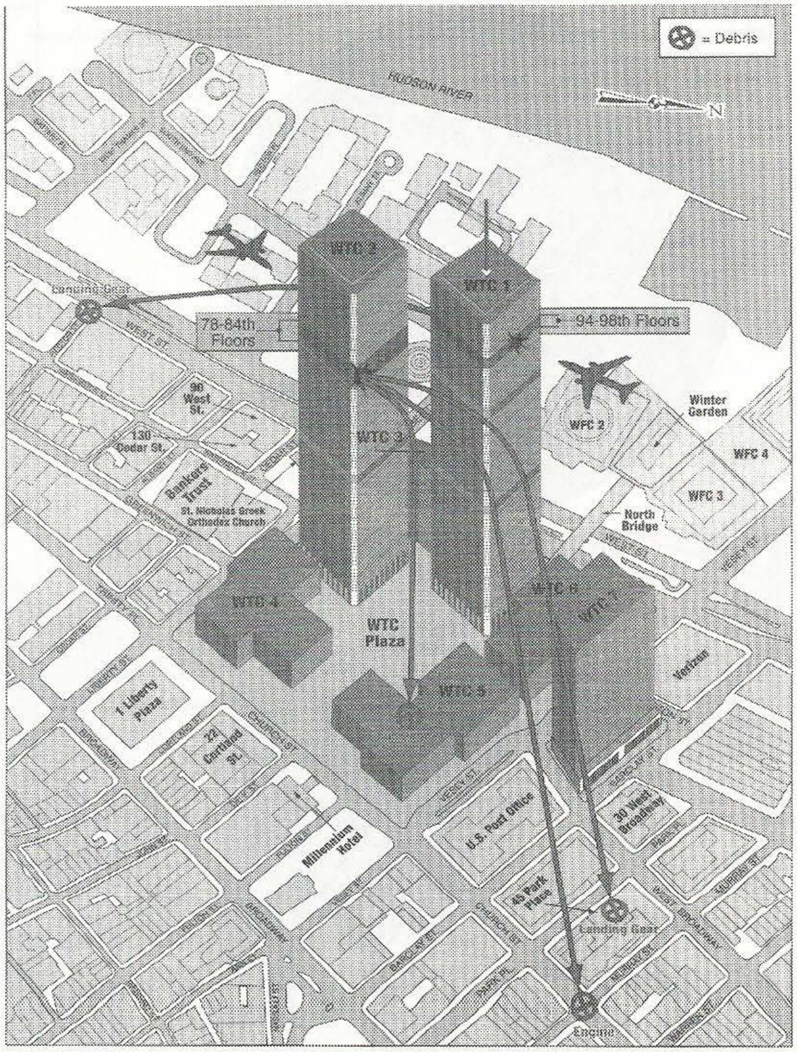

⊗ = Debris
HUDSON RIVER
N
WTC 2
WTC 1
Landing Gear
78-84th Floors
94-98th Floors
WEST ST
90 West St.
130 Cedar St.
Bankers Trust
St. Nicholas Greek Orthodox Church
WTC 3
WFC 2
Winter Garden
WFC 4
WFC 3
North Bridge
VESEY ST
WTC 4
WTC Plaza
WTC 6
WTC 7
Verizon
1 Liberty Plaza
22 Cortlandt St.
LIBERTY ST
BROADWAY
CHURCH ST
Millenium Hotel
WTC 5
U.S. Post Office
30 West Broadway
BARCLAY ST
PARK PL
45 Park Place
Landing Gear
MURRAY ST
WEST BROADWAY
Engine

Figure 1-4 Areas of aircraft debris impact.

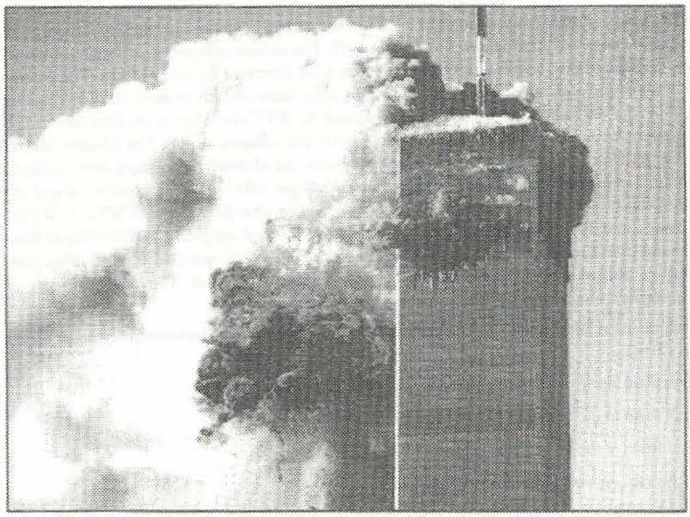


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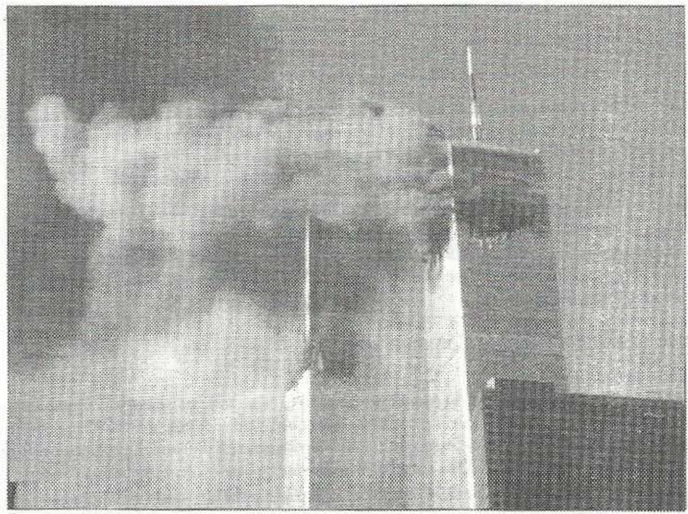
Figure 1-5 Fireball erupts on the north face of WTC 2 as United Airlines Flight 175 strikes the building.



OEM

Figure 1-6 View of the north and east faces showing fire and impact damage to both towers.

Debris from the collapsing towers, some of it still on fire, rained down on surrounding buildings, causing structural damage and starting new fires (Figure 1-7). The sudden collapse of each tower sent out air pressure waves that spread dust clouds of building materials in all directions for many blocks. The density and pressure of the dust clouds were strong enough to carry light debris and lift or move small vehicles and break windows in adjacent buildings for several blocks around the WTC site. Most of the fires went unattended as efforts were devoted to rescuing those trapped in the collapsed towers. The 22-story Marriott World Trade Center Hotel (WTC 3) was hit by a substantial amount of debris during both tower collapses. Portions of WTC 3 were severely damaged by debris from each tower collapse, but progressive collapse of the building did not occur. However, little of WTC 3 remained standing after the collapse of WTC 1. WTC 4, 5, and 6 had floor contents and furnishings burn completely and suffered significant partial collapses from debris impacts and from fire damage to their structural frames. WTC 7, a 47-story building that was part of the WTC complex, burned unattended for 7 hours before collapsing at 5:20 p.m. The falling debris also damaged water mains around the WTC site at the following locations:

- 20-inch main on West Street, closed to the slurry wall, about midway between Vesey Street and Liberty Street
- 20-inch main along the Financial Center north of the South Link Bridge
- 20-inch main at the corner of Liberty Street and West Street
- main in front of the West Street entrance to 90 West
- 24-inch main on Vesey Street, near West Street
- main at the corner of Vesey Street and West Broadway, near the subway station
- main at the southwest edge of 30 West Broadway
- 16-inch main inside the slurry wall

Damaged mains were located after the collapses, but access was impeded by the collapse debris.

The timeline of the major events is summarized in Table 1.1. The times and seismic data were recorded at the Lamont-Doherty Earth Observatory (LDEO) of Columbia University. The signal duration and Richter Scale magnitudes were included to indicate the relative magnitudes of energy transmitted through the ground between the events. Figure 1-8 shows the accelograms recorded by the observatory during the events.

Other buildings surrounding the WTC plaza were also damaged by falling debris. A few buildings, such as the Bankers Trust building, suffered significant damage but remained standing. Many buildings had their façades and glazing damaged and their interiors blanketed with debris from the collapse of the WTC towers and WTC 7. Figures 1-9A and 1-9B are satellite images of the WTC site taken before and after the September 11 attacks, respectively.

1.4 Response of the Engineering Community

1.4.1 Local Authorities

Immediately after the attacks, it became apparent to the City of New York that there was an enormous need for structural engineering and construction expertise and support. Within hours, the DDC appealed to several construction companies (Bovis/Lend-Lease, AMEC, Turner-Plaza and Tully) and the engineering firm, LZA Technology/Thornton-Tomasetti (LZA) to assist in the search and rescue effort. Mobilization began immediately. A reconnaissance inspection by DDC and LZA took place in the afternoon of September 11. A first round of building inspections was performed on September 12 by engineers from DDC, the NYC Department of Buildings (DoB), and LZA.

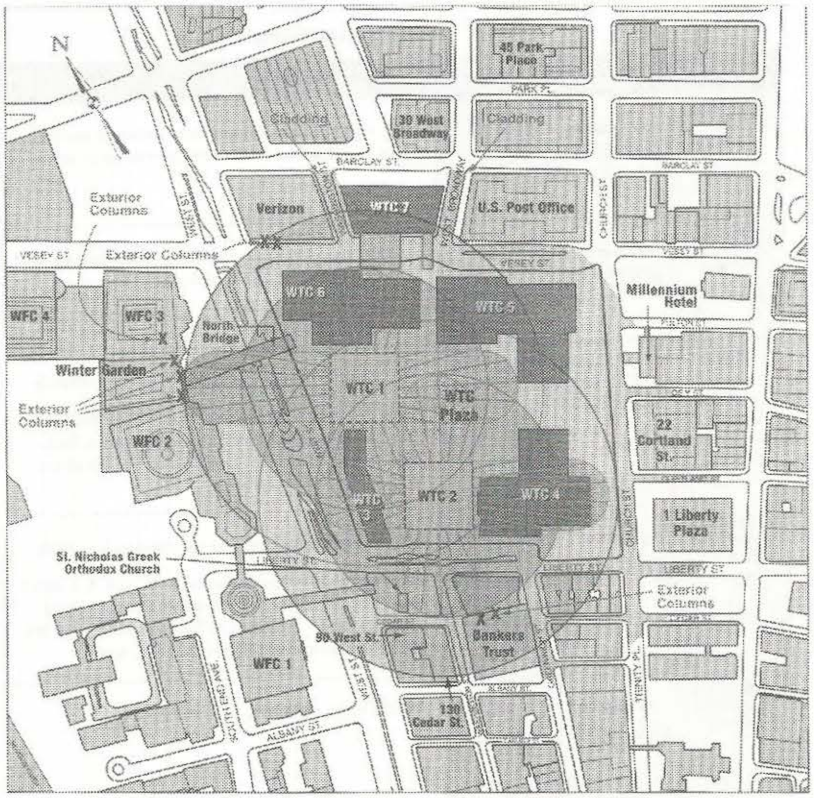
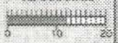
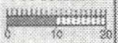
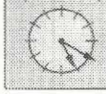
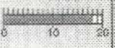

N
45 Park Place
PARK PL
Cladding
30 West Broadway
Cladding
BARCLAY ST.
BARCLAY ST
Exterior Columns
WEST ST.
Verizon
WTC 7
WEST BROADWAY
U.S. Post Office
CHURCH ST
VESEY ST
Exterior Columns
VESEY ST
VESEY ST
Millennium Hotel
WFC 4
WFC 3
North Bridge
WTC 6
WTC 5
Winter Garden
WTC 1
WTC Plaza
Exterior Columns
WFC 2
22 Cortland St.
WTC 3
WTC 2
WTC 4
CHURCH ST
1 Liberty Plaza
St. Nicholas Greek Orthodox Church
LIBERTY ST
LIBERTY ST
LIBERTY ST
Exterior Columns
90 West St.
Bankers Trust
WFC 1
WEST ST
SOUTH END AVE.
ALBANY ST
ALBANY ST
TRINITY PL
130 Cedar St.

Figure 1-7 Schematic depiction of areas of collapse debris impact, based on aerial photographs and documented damage. Striped areas indicate predominant locations of exterior steel columns. Inner circles indicate approximate radius of exterior steel columns and other heavy debris. Outer circles indicate approximate radius of aluminum cladding and other lighter debris. Heavy Xs show where exterior steel columns were found outside the predominate debris areas.

DDC, the agency that had responsibility to manage all construction and engineering at the site, was joined by engineers and construction managers from the Port Authority on the following days. Beginning on September 13, consulting support was provided by SEAoNY, Mueser Rutledge Consulting Engineers, Leslie E. Robertson Associates, the U.S. Army Corps of Engineers, FEMA Urban Search and Rescue, and various other New York City departments.

The engineering efforts had two objectives – safety of personnel involved in the recovery process and evaluation of the conditions and processes that would allow a return to safe occupancy of the buildings in the area.

Table 1.1 Timeline of Major Events[1]

Start Time[2]	Signal Duration	Magnitude (Richter Scale)	Event
8:46:26 EDT (12:46 UTC) 	**12 seconds**  	**0.9**	WTC 1 (the north tower) was hit by American Airlines Flight 11, a hijacked 767-200ER commercial jet airliner.
9:02:54 EDT (13:02 UTC) 	**6 seconds** 	**0.7**	WTC 2 (the south tower) was hit by United Airlines Flight 175, also a hijacked 767-200ER jet.
9:59:04 EDT (13:59 UTC) 	**10 seconds**  	**2.1**	WTC 2 began collapsing after 56 minutes, 10 seconds. Large debris from the collapse fell on WTC 3 and WTC 4, 130 Cedar Street, 90 West Street, and Bankers Trust. WTC 3 suffered a partial collapse. Fire was initiated in WTC 4 and 90 West Street.
10:28:31 EDT (14:28 UTC) 	**8 seconds** 	**2.3**	WTC 1 began collapsing after 102 minutes, 5 seconds. Large debris from the collapse fell on WTC 3, 5, 6, and 7; the Winter Garden; and the American Express (World Financial Center 2) building. WTC 3 collapsed to the 3rd floor, and fires were initiated in WTC 5, 6, and 7.
17:20:33 EDT (21:20 UTC) 	**18 seconds**  	**0.6**	WTC 7 began collapsing.

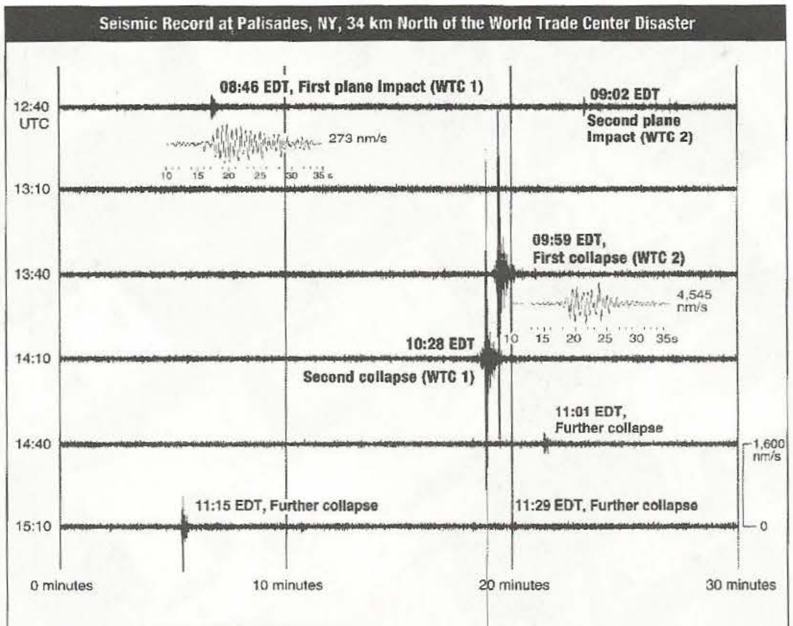
[1] Based on seismic recordings made by the Lamont-Doherty Earth Observatory of Columbia University, 34 kilometers north of the WTC site.

[2] EDT = Eastern Daylight Time; UTC = Coordinated Universal Time. Times cited in this report are based on these times, rounded to the nearest minute.

1.4.2 SEAoNY Participation

Immediately after the attacks, members of the Board of Directors of SEAoNY initiated contact with DDC, DoB, and OEM. By Wednesday morning, September 12, the Board had established communications with the New York Police Department (NYPD), OEM, and DDC. SEAoNY teams of structural engineers were retained through their firms by LZA and began assisting with the rescue and recovery efforts on Thursday, September 13. They served continuously (24 hours a day, 7 days a week) through January 9, 2002. The SEAoNY teams provided engineering guidance with search and rescue, demolition, and temporary construction, as well as assistance to contractors working to stabilize or remove debris.

Seismic Record at Palisades, NY, 34 km North of the World Trade Center Disaster



Record start time: 09/11/2001 08:40 EDT, 12:40 UTC
East-West component of motion at PAL, filtered 0.6 - 5 Hz

LDEO, Columbia University

Figure 1-8 Seismic recordings on east-west component at Palisades, NY, for events at WTC on September 11, 2001, distance 34 km. Three hours of continuous data are shown starting at 08:40 EDT (12:40 UTC). The two largest signals were generated by the collapses of towers 1 and 2. Expanded views of first impact and first collapse are shown in red. The amplitude of the seismic signal is in nanometers per second (nm/s), and the peak amplitude of the ground motion at this station reached to 4,545 nm/s for the first collapse. Note the relatively periodic motions for impacts 1 and 2.

Structural engineers acted as guides through the site, providing descriptions of structures and offering judgment on the stability of structures and debris. They provided warnings of potential hazards and assisted with choosing crane and other equipment locations and installations. Assisting the LZA team, structural engineers worked in four teams staffed by SEAoNY members. In the first 30 days after the attack, more than 10,000 engineer hours, or 1-1/2 engineer-years per week, were expended by these teams.

DDC was also asked on September 14 to rapidly assess the condition of the more than 400 buildings in lower Manhattan suspected of being damaged by the collapse of the WTC towers. It appeared that the zone of damage was significant and that many buildings may have received debris or vibration damage. The potentially hazardous conditions would make the area unsafe for rescue and removal personnel. DDC and LZA assigned this task to SEAoNY. These systematic building inspections were organized, coordinated, and performed by members of SEAoNY. Engineering firms representing those members worked as consultants to

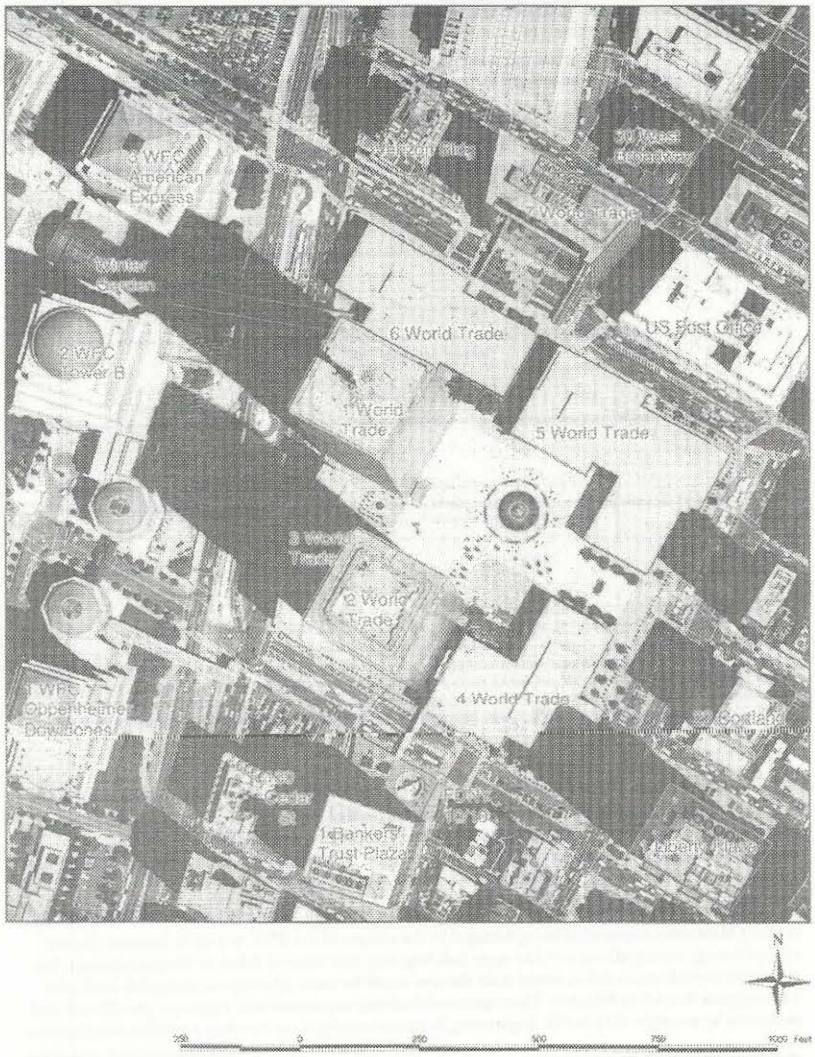

3 WFC
American
Express
Winter
Garden
7 World Trade
US Post Office
6 World Trade
2 WFC
Tower B
1 World
Trade
5 World Trade
3 World
Trade
2 World
Trade
4 World Trade
1 WFC
Oppenheimer
Dow Jones
1 Bankers
Trust Plaza
Liberty Plaza
N
250
0
250
500
750
1000 Feet

Figure 1-9A Satellite photograph of the WTC site taken before the attacks

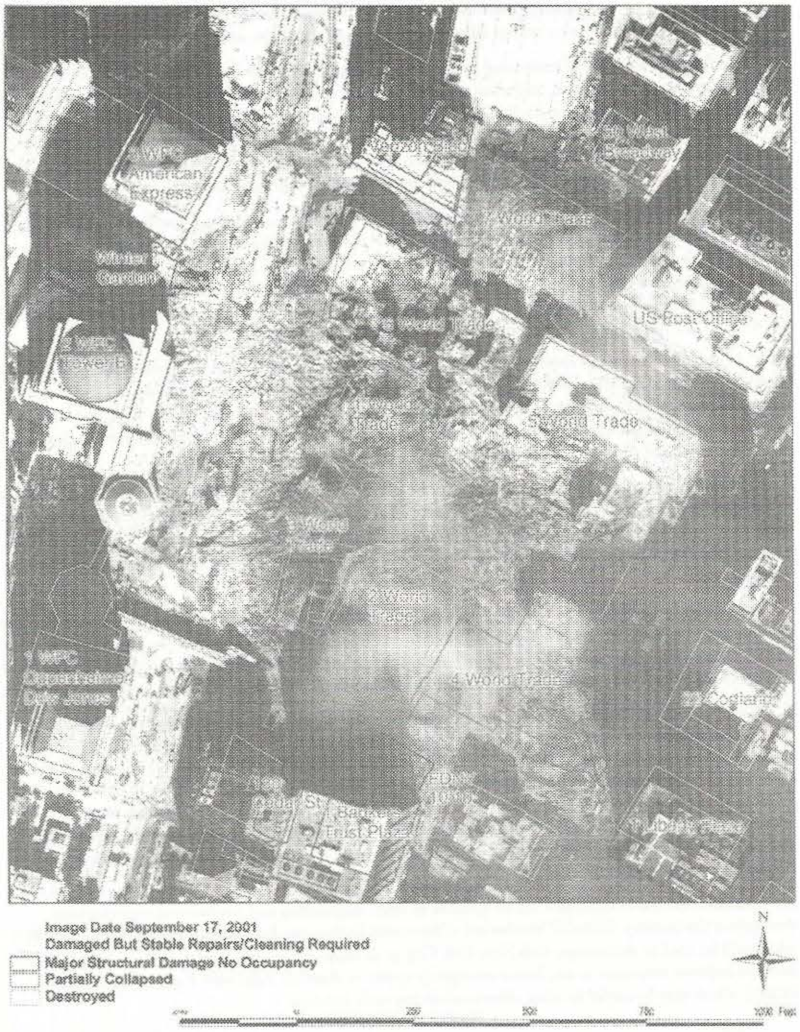

3 WFC
American
Express
Winter
Garden
2 WFC
Tower B
30 West
Broadway
7 World Trade
US Post Office
World Trade
5 World Trade
Trade
3 World
Trade
2 World
Trade
4 World Trade
1 WFC
Oppenheimer
Dow Jones
22 Cortlandt
130
Cedar St
Bankers
Trust Plaza
FDNY
10/10
1 Liberty Plaza
Image Date September 17, 2001
Damaged But Stable Repairs/Cleaning Required
Major Structural Damage No Occupancy
Partially Collapsed
Destroyed
N
250
500
750
1000 Feet

Figure 1-9B Satellite photograph of the WTC site taken after the attacks.

LZA. The purpose of the building assessment was to assist in determining which buildings could be safely reoccupied and to identify structural or falling hazards that might injure site personnel or the public.

Similar efforts had been conducted by Structural Engineers Associations in the western United States following earthquakes; however, no formal mechanisms were in place in New York for this type of effort. The field manual *ATC 20, Procedures for Post-earthquake Safety Evaluation of Buildings*, published by the Applied Technology Council (ATC) was used for procedural guidance on performing the inspections. Custom forms for rapid visual assessments were created. Additional teams of structural engineers organized by SEAoNY completed the first round of assessments of approximately 400 buildings on September 17 and 18.

After the initial assessments had been completed, additional inspections were recommended for the buildings that appeared to be the most distressed. These additional inspections were completed within a matter of days after the recommendations were discussed with DDC. As a follow-up, a second round of evaluations for all of the buildings was performed between October 4 and 10, and detailed engineering reports for the most severely damaged buildings (outside of the WTC site) were prepared in conjunction with DDC and LZA. Building evaluation summaries are presented in Chapter 7 (Peripheral Buildings).

In the initial response, most of SEAoNY's members volunteered, as did structural engineers from across the country who coordinated with SEAoNY through NCSEA. SEAoNY members located in New York City also volunteered office space, equipment, and support to other engineers working at the WTC site. To eliminate any potential liability issues and to meet the long-term commitment required by the engineers due to the magnitude of the event, all of these engineers were retained by DDC through LZA.

SEAoNY volunteers provided assistance to the BPS Team by maintaining five teams of structural engineers to monitor steel debris from the WTC site as it arrived at the salvage yards. Their goal was to locate material from the impact zones. SEAoNY engineers also collected hundreds of hours of video and thousands of still photographs from other engineers and the general public in an effort to fully document the collapses and the recovery operations.

As with any first-time event, difficulties were encountered at the beginning of the relationship between the volunteer engineering community and the local government agencies. There were no procedures for either the engineers or the agencies to follow for such an event, leading to a situation in which the organization of the work and the procedures to be followed were developed and revised almost daily in response to the circumstances.

Issues of identification, credentials, responsibility, and liability required considerable attention. Because the site was treated as a crime scene, access at various locations had to be obtained through checkpoints manned by the National Guard, the Fire Department of New York (FDNY), and the NYPD. Also, because there was no identification system in place for the first few days, it took up to 3 hours for SEAoNY volunteers to get to the command center from the outer perimeter of the site, a distance of less than six blocks. In addition, there were issues related to the responsibilities and liabilities of individual volunteers, their firms, and SEAoNY. Currently in New York City, there is no process for deputizing volunteers, nor are there any "Good Samaritan" laws in effect.

Lessons learned in hindsight can be valuable to other engineering and professional organizations throughout the country. SEAoNY has drafted a "Structural Engineering Emergency Response Plan (SEERP)," which will be used in discussions with New York City to develop and formalize relationships and procedures that will improve responses to any future emergency events or disasters. Appendix F presents the draft SEERP, which may be useful to other cities considering such activities.

1.5 Overview of Building Codes and Fire Standards

1.5.1 Building Codes

Building design and occupancy in the United States is governed by building codes that specify the minimum environmental, or external, loads that a building must have the strength to resist. They also prescribe requirements for internal challenges such as fire protection and timely egress for life safety. However, designers must consider project circumstances and owner requirements when determining building design loads. The primary external loads specified are:

- gravity
- wind
- earthquake

Other risks considered include the potential for fire, hazardous material leaks or explosion, and the need to promptly evacuate occupants to safety. These demands establish building code requirements for fire resistive construction, emergency egress, and fire protection systems.

National model building codes do not include requirements to design for loads that might be imposed due to acts of war or terrorism. It is usually considered unnecessary to provide the capacity to resist such loads in most buildings; however, these loads may be included at the discretion of building owners if they desire a higher level of protection (e.g., an embassy, bank, or military facility).

Gravity loads include both the weight of the building and its contents. The weight of the building is calculated based on building construction plans and material densities. The weight of the contents is not specifically known at the time of design because it will depend on the building user and will vary with time. Therefore, the codes specify minimum floor loads on a pounds per square foot basis. For instance, for a standard office occupancy, the codes typically specify a minimum live load of 50 pounds per square foot (psf) of floor area. It is the responsibility of the building owners to see that floors are not overloaded.

Wind loads specified by codes are based on maps of design wind speed for different regions of the country. As wind speed increases, the wind pressure on the building increases proportionally to the square of the wind velocity. The pressure on the building also varies with the height and degree of shielding provided by other buildings and geographic features. Although not usually required by building codes, engineers frequently use wind tunnel studies to more accurately determine wind loads on tall buildings, where standard calculations may not be adequate. WTC 1, 2, 4, 5, and 6 all had extensive wind tunnel studies performed as part of the design process. WTC 1 and WTC 2 were among the first structures that were designed using wind tunnel studies.

The hazard presented by earthquakes is also highly dependent on the geographic region. In all regions of the country, including the most severe seismic areas of California, the effects of earthquakes are relatively small for very tall buildings. The flexibility of a very tall building, say 100 stories, generally allows the building to respond as the ground moves back and forth without developing forces nearly as large as those produced by design wind loads. Therefore, even in a severe seismic area, tall building design is generally controlled by wind loads.

Engineers design buildings for gravity, wind, and earthquake loads. Architects, in concert with fire protection professionals, including fire protection engineers, oversee the selection and application of fire resistive construction elements and fire protection systems such as sprinklers, fire alarms, and special hazard protection.

The building codes also prescribe the minimum requirements for life safety if a fire occurs. The prescribed fire safety features are intended to limit the fire threat and safeguard those in the building. Prime among these features are the egress and emergency notification (alarm) requirements.

Particularly in high-rise buildings, fire safety requirements are prescribed to maintain the integrity of the structure by controlling the intensity of fire and providing adequate structural strength during fires. In modern building codes, this is accomplished through a three-step approach:

- The first line of defense is the automatic sprinkler protection designed to control fires in their early stage of development and either extinguish them or hold the fire in check for the arrival of the fire department. Sprinklers are not normally capable of controlling fires that are of large size before the sprinklers can operate. Such was the case in the twin towers.
- The second line of defense is manual firefighting by the fire department or fire brigades. The building is provided with standpipes, emergency control of elevators, special emergency communication systems, control centers, and other features to enable effective firefighting above the levels that can be attacked from the exterior. It was this line of defense that successfully controlled the 1975 fire. In the September 11 incident, the damage done to the elevators and the height of the fires precluded the fire department from being able to directly attack the fire. Even if they had reached the fire floors, they would have been faced with a fire situation possibly beyond even the excellent capabilities of the FDNY.
- The final line is the fire resistance of the building and its elements, including the building frame, the floors, partitions, shaft enclosures, and other elements that compartmentalize the building and structurally support it. Most important of these are the requirements for the structural frame (including columns, girders, and trusses). See Section 1.5.3 for a discussion of fire resistance ratings.

All three of these lines of defense were present, but were overwhelmed by the magnitude of the events of September 11, 2001.

For life safety and egress, stairways must have minimum widths based on the maximum number of occupants who may be in the building. Stairs must be separated from the remainder of the building by a minimum 1- or 2-hour fire resistant barrier to provide a level of safety while occupants traverse the stairs. At least two stairways must be provided with widely separated entry points. In most jurisdictions, elevators are designed to automatically return to the lobby level during a fire alarm to be controlled by firefighters. In many high-rise buildings, the elevator shafts and exit stairs are pressurized to keep out smoke and heat. The use of elevators is discouraged for emergency egress because of the potential for elevator failure and the likelihood of the elevator shaft acting like a chimney, carrying heat, smoke, and toxic gases throughout the building.

Fire protection systems (sprinklers, fire alarms, and special-hazard protection) are required to provide early notification and fire control until the fire department can arrive and begin manual suppression efforts. Smoke management systems are intended to aid emergency evacuation of building occupants and operations of emergency personnel. Manual suppression efforts by emergency personnel are aided by the presence of standpipe systems.

1.5.2 Unusual Building Loads

In planning a new building, an owner may request enhanced requirements in its design for events that are not anticipated by the building codes. In some cases, where unusual hazards such as explosive or toxic materials exist, the building codes prescribe special life safety and fire protection features. In most non-hazardous occupancies, these are not required. Only a very small percentage of buildings have extraordinary provisions for unusual circumstances and there is a limit to the events that can be handled and the strength capacities that can be provided. Defense facilities, nuclear power plants, and overseas embassies are just a few examples where special strengthening features are requested by building owners in the design and engineering of their facilities.

The WTC towers were the first structures outside of the military and the nuclear industries whose design considered the impact of a jet airliner, the Boeing 707. It was assumed in the 1960s design analysis for the WTC towers that an aircraft, lost in fog and seeking to land at a nearby airport, like the B-25 Mitchell bomber that struck the Empire State Building on July 28, 1945, might strike a WTC tower while low on fuel and at landing speeds. However, in the September 11 events, the Boeing 767-200ER aircraft that hit both towers were considerably larger with significantly higher weight, or mass, and traveling at substantially higher speeds. The Boeing 707 that was considered in the design of the towers was estimated to have a gross weight of 263,000 pounds and a flight speed of 180 mph as it approached an airport; the Boeing 767-200ER aircraft that were used to attack the towers had an estimated gross weight of 274,000 pounds and flight speeds of 470 to 590 mph upon impact.

Including aircraft impact as a design load requires selecting a design aircraft, as well as its speed, weight, fuel, and angle and elevation of impact. Figure 1-10 compares the design characteristics of several large aircraft that were in use or being planned for use during the life of the WTC towers. The maximum takeoff weight, fuel capacity, and cruise speed shown for each class of aircraft are presented for comparison of relative sizes and speeds. The larger square represents the floor plan area of the WTC towers (approximately 207 feet by 207 feet), and the smaller square represents a more typical size for a high-rise building. The likelihood of a building surviving an aircraft impact decreases as aircraft size and speed increase. The Airbus A380 is expected to be flying in 2006. Its weight and fuel capacity are approximately three times those of a 767-200ER. The security of aircraft is critical to the safety of high-rise and all other buildings; aircraft security measures should be commensurate with the size and potential risk posed by the aircraft.

The decision to include aircraft impact as a design parameter for a building would clearly result in a major change in the design, livability, usability, and cost of buildings. In addition, reliably designing a building to survive the impact of the largest aircraft available now or in the future may not be possible. These types of loads and analyses are not suitable for inclusion in minimum loads required for design of all buildings. Just as the possibility of a Boeing 707 impact was a consideration in the original design of WTC 1 and WTC 2, there may be situations where it is desirable to evaluate building survival for impact of an airplane of a specific size traveling at a specific speed. Although there is limited public information available on this topic (Bangash 1993, DOE 1996), interested building owners and design professionals would require further guidance for application to buildings.

1.5.3 Overview of Fire-Structure Interaction

Control of structural behavior under fire conditions has historically been based on highly prescriptive building code requirements. These requirements specify hourly fire resistance ratings. A popular misconception concerning fire resistance ratings for walls, columns, floors, and other building components is that the ratings imply the length of time that a building component will remain in place when exposed to an actual fire. For example, a 2-hour fire-resistant wall is often expected to remain standing for 2 hours if exposed to an actual fire. However, the time to collapse of such a wall in an actual fire may be greater or less than 2 hours. The standard method of test to evaluate fire resistance (ASTM E119) is a comparative test of relative specimen behavior under controlled conditions and is not intended to be predictive of actual behavior. Further, the results of the ASTM E119 test do not consider actual conditions such as member interactions, restraint, connections, or situations where damage to the structural assembly is present prior to initiation of the fire.

1.5.3.1 ASTM E119 Standard Fire Test

Building code requirements for structural fire protection are based on laboratory tests conducted in accordance with the Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM E119 (also designated NFPA 251 and UL 263). Since its inception in 1918, the ASTM E119 Standard Fire Test has required that test specimens be representative of actual building construction. Achieving this requirement in actual practice has been difficult because available laboratory facilities can only accommodate floor specimens on the order of a 14-foot x 17-foot (4.3-meter x 5.2-meter) plan area in a fire test furnace. The specimens do not account for impact damage to fire protection coatings. For typical steel and concrete structural systems, the behavior of specimens in an ASTM E119 fire test does not reflect the behavior of floor and roof constructions that are exposed to uncontrolled fire in real buildings. The ASTM E119 fire endurance test exposes the test specimen to the time-temperature relationship shown in Appendix A, Figure A-9.

In contrast with the structural characteristics of ASTM E119 test specimens, floor slabs in real buildings are continuous over interior beams and girders, connections range from simple shear to full moment connections, and framing member size and geometry vary significantly, depending on structural system and building size and layout. Even for relatively simple structural systems, realistically simulating the restraint, continuity, and redundancy present in actual buildings is extremely difficult to achieve in a laboratory fire test assembly. In addition, the size and intensity of a real uncontrolled fire and the loads superimposed on a floor system during that exposure are variables not investigated during an ASTM E119 fire test. Many factors influence the intensity and duration of an uncontrolled fire and the likelihood of full design loads occurring simultaneously with peak fire temperatures is minimal.

The ASTM E119 Standard Fire Test was developed as a comparative test, not a predictive one. In effect, the Standard Fire Test is used to evaluate the relative performance (fire endurance) of different construction assemblies under controlled laboratory conditions, not to predict performance in real, uncontrolled fires.

1.5.3.2 Performance in Actual Building Fires

Extensive fire research in the United States and the international community established that the temperatures generated during an actual fire, represented by a time-temperature curve, is not only a function of the fire load, but also the following:

- ventilation (air access through the windows, doors, and heating, ventilation, and air conditioning [HVAC] system)
- compartment geometry (floor area, ceiling height, length to width to height ratios)
- thermal properties of the walls, floor, and ceiling construction
- combustion characteristics of the fuel (rate and duration of heat release)

International research in the past 30 years has substantiated the importance of ventilation rates. It is now recognized that two entirely different types of fires can occur within buildings or compartments. The first is a "fuel surface controlled fire" that will develop when compartment openings are sufficiently large to provide adequate combustion air for unrestricted burning. Such fires will generally be of short duration and the intensity will be controlled by the fire load and its arrangement.

The second type of fire is "ventilation controlled" and will develop when the compartment openings are not large enough to allow unrestricted burning. Such fires will burn longer than fires controlled by the amount of surface fuel. Fires in large spaces often burn in ventilation controlled and fuel surface controlled regimes, at different times during the fire and at different locations within the enclosure.

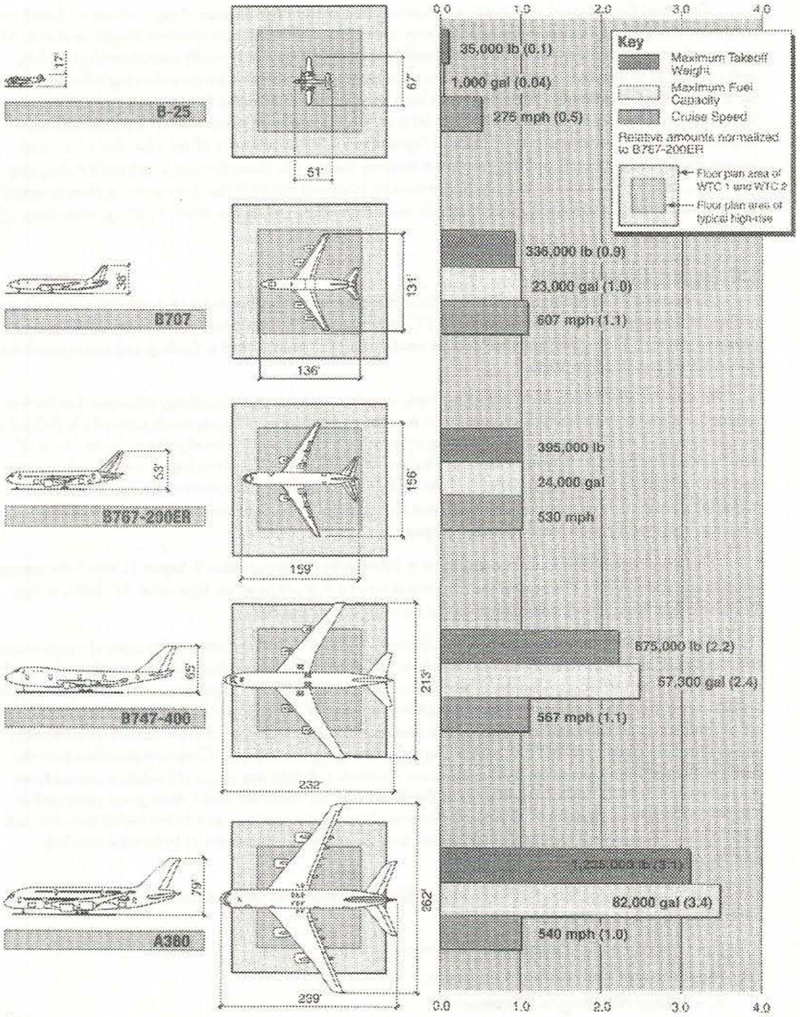


Figure 1-10 Comparison of high-rise building and aircraft sizes.

These real fires contrast with building code requirements for fire resistant design, which are based on a presumed duration of a standard fire as a function of fire load and building occupancy, height, and area. The severity of actual fires is determined by additional factors, which are not typically considered in building codes except as an alternate material method or equivalency when accepted by the enforcing official (the authority having jurisdiction). Although there have been a number of severe fires in protected steel buildings, including the three described in Appendix A, Section A.3.1.3, the team is unaware of any protected steel structures that have collapsed in a fire prior to September 11. However, none of the other fire events had impact damage to structural and fire protection systems. Recent fire research provides a basis for designing more reliable fire protection for structural members by analytical methods that are becoming more acceptable to the building code community. Such methods were not available when the WTC buildings were designed in the 1960s.

1.6 Report Organization

All seven WTC buildings, the Bankers Trust building, and other buildings that sustained major impact and/or fire damage from the attacks on the WTC towers are discussed in detail in this report. Information is presented about building performance documented during this study, as well as findings and recommendations for each building, as appropriate.

In order to simultaneously conduct multiple investigations into each building, a Chapter Leader was assigned as a lead coordinator and author for each chapter or appendix. This approach allowed a high level of productivity and resulted in a different writing style for each chapter. Additionally, the scope and level of detail varies considerably between chapters. The two major factors that define chapter content are the type and level of damage a building suffered and the availability of building information during this study, including damage documentation, structural and architectural plans, fire protection systems, building contents, and modifications made during occupancy.

This report opens with an executive summary, followed by the Introduction (Chapter 1), which documents the purpose and scope of this report; the events and actions that occurred on September 11, 2001, at the WTC site; and background information on the building design and codes.

The WTC buildings are presented in Chapters 2 through 5, and are grouped by types of construction and damage. Chapter 2 presents observations, data, and the results of preliminary analyses conducted on each tower (WTC 1 and WTC 2). Chapter 3 briefly discusses the hotel (WTC 3) performance for two severe debris impact events from the collapsing towers. Chapter 4 includes WTC 4, 5, and 6, because all three buildings are of similar construction and experienced fire damage from debris. Chapter 5 presents observations, data, and preliminary analyses of WTC 7, which also suffered a complete collapse. Chapter 6 describes how the Bankers Trust building arrested a local collapse on the north side that was initiated by debris impact from the collapse of WTC 2. Buildings adjacent to the WTC site that sustained major damage are presented in Chapter 7 (Peripheral Buildings). Chapter 8 presents observations, findings, and recommendations for each building, as well as overall recommendations based on the collective assessment of individual building performance and related issues.

The following appendixes are included to allow development of pertinent issues and topics without interrupting the flow of the report:

A – Overview of Fire Protection in Buildings

B – Structural Steel and Steel Connections

C – Limited Metallurgical Examination

D – WTC Steel Data Collection

E – Aircraft Information

F – Structural Engineers Emergency Response Plan

G – Acknowledgments

H – Acronyms and Abbreviations

I – Metric Conversions

The reader should be aware that English units are the primary system of measurement in this report, except where temperature information is presented, such as in the discussion of fire protection systems. Temperatures are presented in degrees Celsius, followed by degrees Fahrenheit. This approach allows for ease of reading by general audiences while retaining the measurement system preferred by fire protection engineers.

1.7 References

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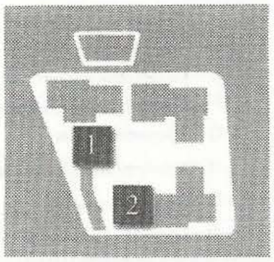
Ronald Hamburger
William Baker
Jonathan Barnett
James Milke
Harold "Bud" Nelson



2 WTC 1 and WTC 2

2.1 Building Descriptions

2.1.1 General

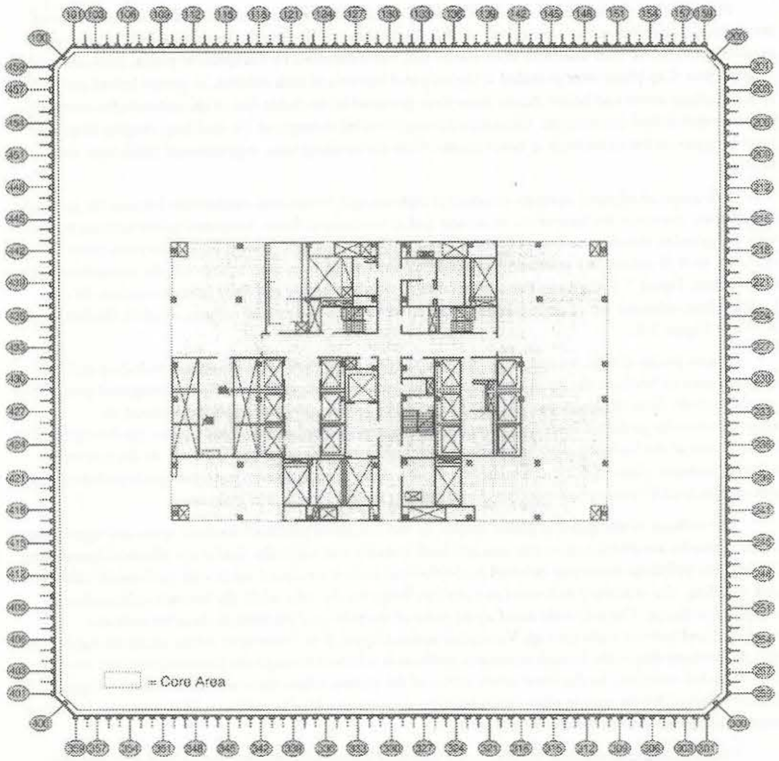
The WTC towers, also known as WTC 1 and WTC 2, were the primary components of the seven-building World Trade Center complex. Each of the towers encompassed 110 stories above the Plaza level and seven levels below. WTC 1 (the north tower) had a roof height of 1,368 feet, briefly earning it the title of the world's tallest building. WTC 2 (the south tower) was nearly as tall, with a roof height of 1,362 feet. WTC 1 also supported a 360-foot-tall television and radio transmission tower. Each building had a square floor plate, 207 feet 2 inches long on each side. Corners were chamfered 6 feet 11 inches. Nearly an acre of floor space was provided at each level. A rectangular service core, with overall dimensions of approximately 87 feet by 137 feet, was present at the center of each building, housing 3 exit stairways, 99 elevators, and 16 escalators. Figure 2-1 presents a schematic plan of a representative aboveground floor.

The project was developed by the Port Authority of New York and New Jersey (hereafter referred to as the Port Authority), a bi-state public agency. Original occupancy of the towers was dominated by government agencies, including substantial occupancy by the Port Authority itself. However, this occupancy evolved over the years and, by 2001, the predominant occupancy of the towers was by commercial tenants, including a number of prominent financial and insurance services firms.

Design architecture was provided by Minoru Yamasaki & Associates, and Emery Roth & Sons served as the architect of record. Skilling, Helle, Christiansen, Robertson were the project structural engineers; Jaros, Baum & Bolles were the mechanical engineers; and Joseph R. Loring & Associates were the electrical engineers. The Port Authority provided design services for site utilities, foundations, basement retaining walls, and paving. Groundbreaking for construction was on August 5, 1966. Steel construction began in August 1968. First tenant occupancy of WTC 1 was in December 1970, and occupancy of WTC 2 began in January 1972. Ribbon cutting was on April 4, 1973.

2.1.2 Structural Description

WTC 1 and WTC 2 were similar, but not identical. WTC 1 was 6 feet taller than WTC 2 and also supported a 360-foot tall transmission tower. The service core in WTC 1 was oriented east to west, and the service core in WTC 2 was oriented north to south. In addition to these basic configuration differences, the presence of each building affected the wind loads on the other, resulting in a somewhat different distribution of design wind pressures, and, therefore, a somewhat different structural design of the lateral-force-resisting system. In addition, tenant improvements over the years resulted in removal of portions of floors and placement of new private stairways between floors, in a somewhat random pattern. Figure 2-2 presents a structural framing plan representative of an upper floor in the towers.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= Core Area

Figure 2-1 Representative floor plan (based on floor plan for 94th and 95th floors of WTC 1).

The buildings' signature architectural design feature was the vertical fenestration, the predominant element of which was a series of closely spaced built-up box columns. At typical floors, a total of 59 of these perimeter columns were present along each of the flat faces of the building. These columns were built up by welding four plates together to form an approximately 14-inch square section, spaced at 3 feet 4 inches on center. Adjacent perimeter columns were interconnected at each floor level by deep spandrel plates, typically 52 inches in depth. In alternate stories, an additional column was present at the center of each of the chamfered building corners. The resulting configuration of closely spaced columns and deep spandrels created a perforated steel bearing-wall frame system that extended continuously around the building perimeter.

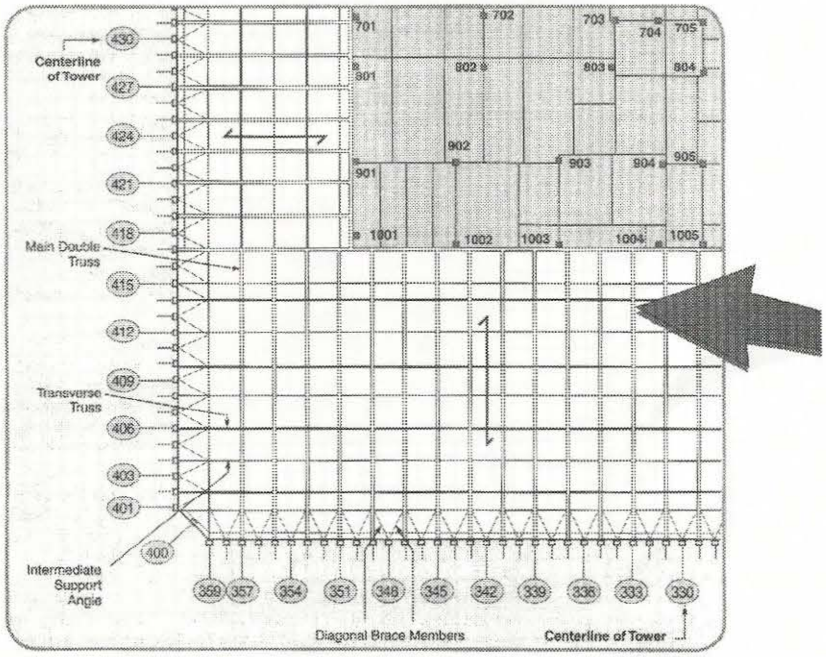
Figure 2-3 presents a partial elevation of this exterior wall at typical building floors. Construction of the perimeter-wall frame made extensive use of modular shop prefabrication. In general, each exterior wall module consisted of three columns, three stories tall, interconnected by the spandrel plates, using all-welded construction. Cap plates were provided at the tops and bottoms of each column, to permit bolted connection to the modules above and below. Access holes were provided at the inside face of the columns for attaching high-strength bolted connections. Connection strength varied throughout the building, ranging from four bolts at upper stories to six bolts at lower stories. Near the building base, supplemental welds were also utilized.

Side joints of adjacent modules consisted of high-strength bolted shear connections between the spandrels at mid-span. Except at the base of the structures and at mechanical floors, horizontal splices between modules were staggered in elevation so that not more than one third of the units were spliced in any one story. Where the units were all spliced at a common level, supplemental welds were used to improve the strength of these connections. Figure 2-3 illustrates the construction of typical modules and their interconnection. At the building base, adjacent sets of three columns tapered to form a single massive column, in a fork-like formation, shown in Figure 2-4.

Twelve grades of steel, having yield strengths varying between 42 kips per square inch (ksi) and 100 ksi, were used to fabricate the perimeter column and spandrel plates as dictated by the computed gravity and wind demands. Plate thickness also varied, both vertically and around the building perimeter, to accommodate the predicted loads and minimize differential shortening of columns across the floor plate. In upper stories of the building, plate thickness in the exterior wall was generally 1/4 inch. At the base of the building, column plates as thick as 4 inches were used. Arrangement of member types (grade and thickness) was neither exactly symmetrical within a given building nor the same in the two towers.

The stiffness of the spandrel plates, created by the combined effects of the short spans and significant depth, created a structural system that was stiff both laterally and vertically. Under the effects of lateral wind loading, the buildings essentially behaved as cantilevered hollow structural tubes with perforated walls. In each building, the windward wall acted as a tension flange for the tube while the leeward wall acted as a compression flange. The side walls acted as the webs of the tube, and transferred shear between the windward and leeward walls through Vierendeel action (Figure 2-5). Vierendeel action occurs in rigid trusses that do not have diagonals. In such structures, stiffness is achieved through the flexural (bending) strength of the connected members. In the lower seven stories of the towers, where there were fewer columns (Figure 2-4), vertical diagonal braces were in place at the building cores to provide this stiffness. This structural frame was considered to constitute a tubular system.

Floor construction typically consisted of 4 inches of lightweight concrete on 1-1/2-inch, 22-gauge non-composite steel deck. In the core area, slab thickness was 5 inches. Outside the central core, the floor deck was supported by a series of composite floor trusses that spanned between the central core and exterior wall. Composite behavior with the floor slab was achieved by extending the truss diagonals above the top chord so that they would act much like shear studs, as shown in Figure 2-6. Detailing of these trusses was similar to that employed in open-web joist fabrication and, in fact, the trusses were manufactured by a joist fabricator, the LaClede Steel Corporation. However, the floor system design was not typical of open-web-joist floor systems. It was considerably more redundant and was well braced with transverse members. Trusses were placed in pairs, with a spacing of 6 feet 8 inches and spans of approximately 60 feet to the sides and 35 feet at the ends of the central core. Metal deck spanned parallel to the main trusses and was directly supported by continuous transverse bridging trusses spaced at 13 feet 4 inches and intermediate deck support angles spaced at 6 feet 8 inches from the transverse trusses. The combination of main trusses, transverse trusses, and deck support enabled the floor system to act as a grillage to distribute load to the various columns.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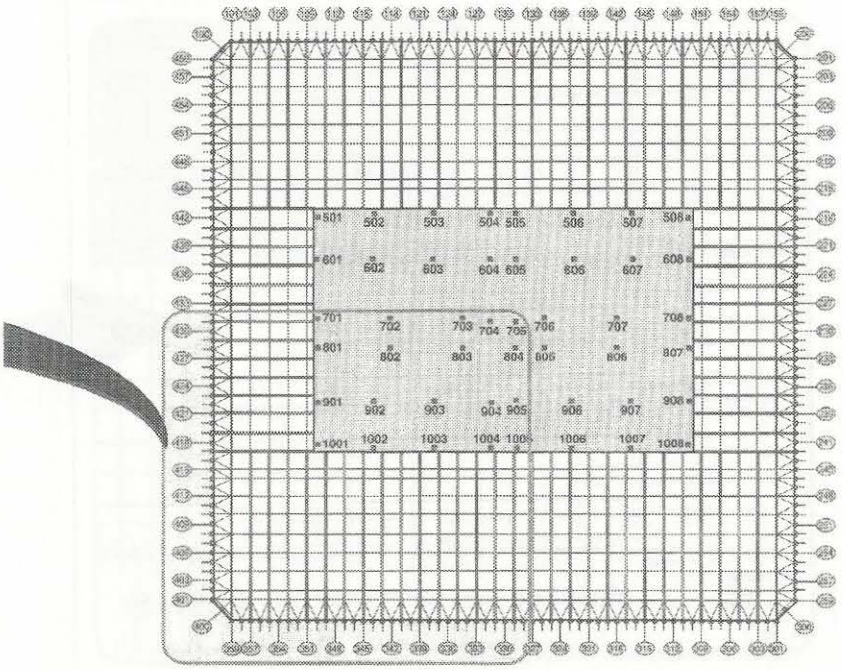
Diagonal Brace Members
Centerline of Tower

Figure 2-2 Representative structural framing plan, upper floors.

At the exterior wall, truss top chords were supported in bearing off seats extending from the spandrels at alternate columns. Welded plate connections with an estimated ultimate capacity of 90 kips (refer to Appendix B) tied the pairs of trusses to the exterior wall for out-of-plane forces. At the central core, trusses were supported on seats off a girder that ran continuously past and was supported by the core columns. Nominal out-of-plane connection was provided between the trusses and these girders. Figures 2-7 and 2-8 illustrate this construction, and Figure 2-9 shows a cross-section through typical floor framing. Floors were designed for a uniform live load of 100 pounds per square foot (psf) over any 200-square-foot area with allowable live load reductions taken over larger areas. At building corners, this amounted to a uniform live load (unreduced) of 55 psf.

At approximately 10,000 locations in each building, viscoelastic dampers extended between the lower chords of the joists and gusset plates mounted on the exterior columns beneath the stiffened seats (Detail A in Figure 2-6). These dampers were the first application of this technology in a high-rise building, and were provided to reduce occupant perception of wind-induced building motion.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Pairs of flat bars extended diagonally from the exterior wall to the top chord of adjacent trusses. These diagonal flat bars, which were typically provided with shear studs, provided horizontal shear transfer between the floor slab and exterior wall, as well as out-of-plane bracing for perimeter columns not directly supporting floor trusses (Figure 2-2).

The core consisted of 5-inch concrete fill on metal deck supported by floor framing of rolled structural shapes, in turn supported by a combination of wide flange shape and box-section columns. Some of these columns were very large, with cross-sections measuring 14 inches wide by 36 inches deep. In upper stories, these rectangular box columns transitioned into heavy rolled wide flange shapes.

Between the 106th and 110th floors, a series of diagonal braces were placed into the building frame. These diagonal braces together with the building columns and floor framing formed a deep outrigger truss system that extended between the exterior walls and across the building core framing. A total of 10 outrigger truss lines were present in each building (Figure 2-10), 6 extending across the long direction of the core and

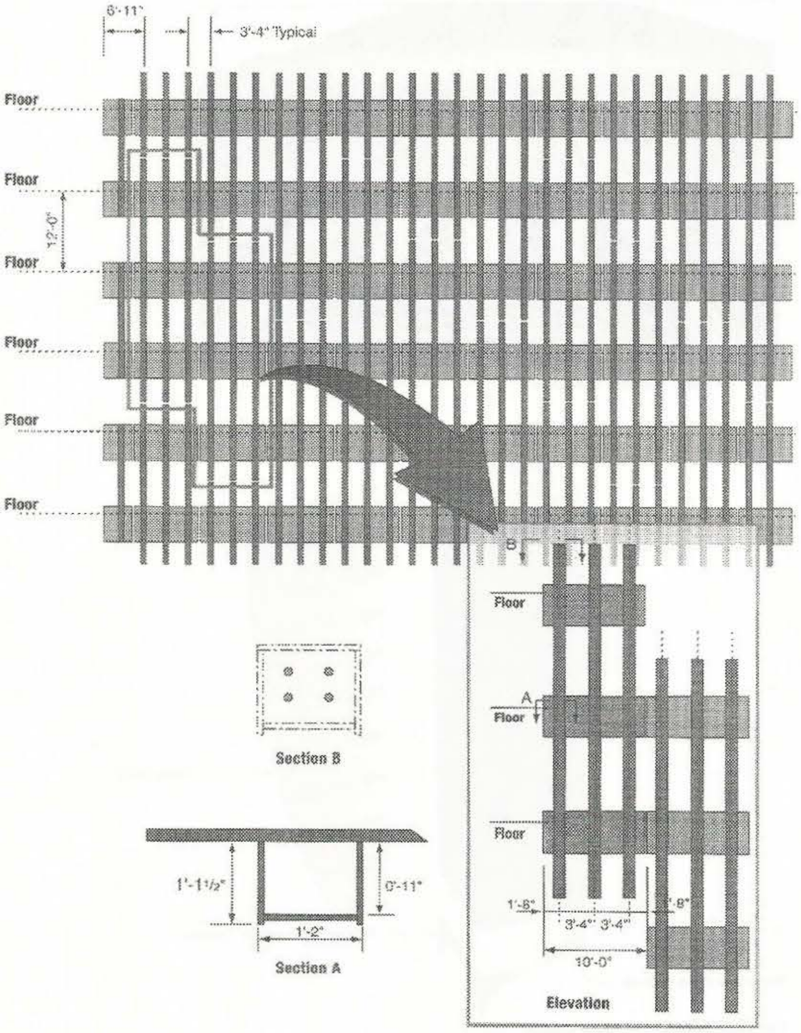

6'-11"
3'-4" Typical
Floor
Floor
12'-0"
Floor
Floor
Floor
Floor
B
Floor
A
Floor
Floor
Section B
1'-1½"
0'-11"
1'-2"
Section A
1'-8"
3'-4"
3'-4"
1'-8"
10'-0"
Elevation

Figure 2-3 Partial elevation of exterior bearing-wall frame showing exterior wall module construction.

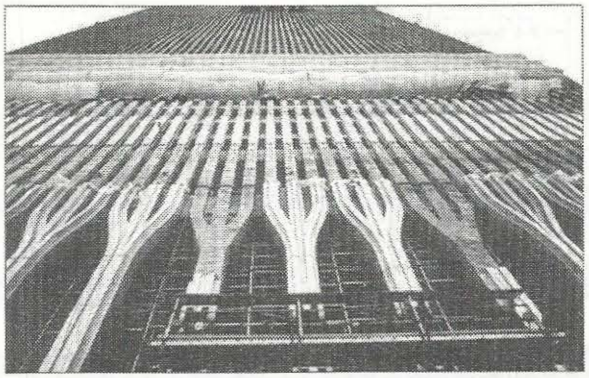
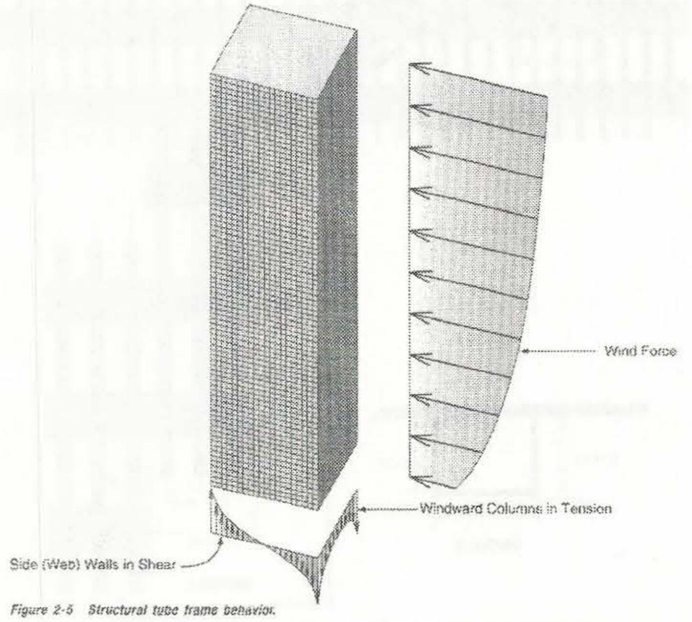


Figure 2-4 Base of exterior wall frame.



Wind Force
Windward Columns in Tension
Side (Web) Walls in Shear

Figure 2-5 Structural tube frame behavior.

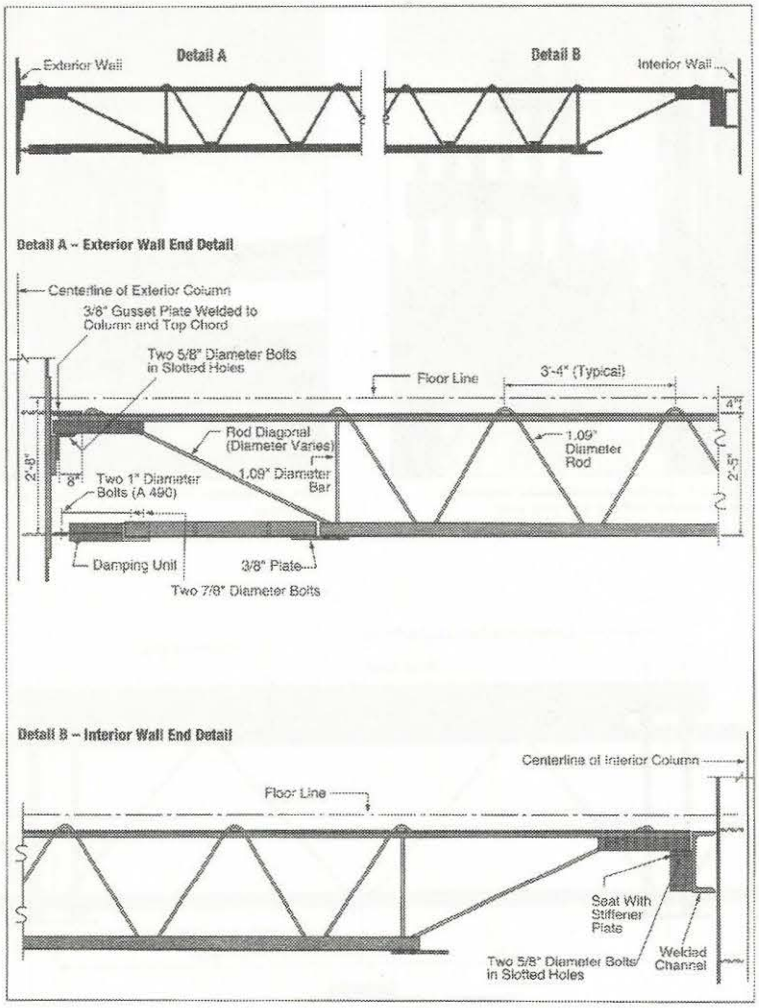

Exterior Wall
Detail A
Detail B
Interior Wall
Detail A – Exterior Wall End Detail
Centerline of Exterior Column
3/8" Gusset Plate Welded to Column and Top Chord
Two 5/8" Diameter Bolts in Slotted Holes
Floor Line
3'-4" (Typical)
4"
Rod Diagonal (Diameter Varies)
1.09" Diameter Rod
2'-8"
8"
Two 1" Diameter Bolts (A 490)
1.09" Diameter Bar
2'-5"
Damping Unit
3/8" Plate
Two 7/8" Diameter Bolts
Detail B – Interior Wall End Detail
Centerline of Interior Column
Floor Line
Seat With Stiffener Plate
Two 5/8" Diameter Bolts in Slotted Holes
Welded Channel

Figure 2-6 Floor truss member with detail of end connections.

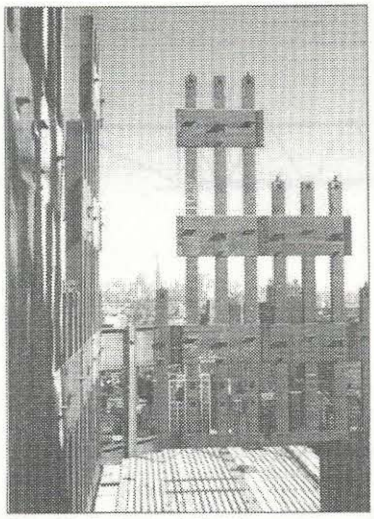


Figure 2-7 Erection of prefabricated components, forming exterior wall and floor deck units.

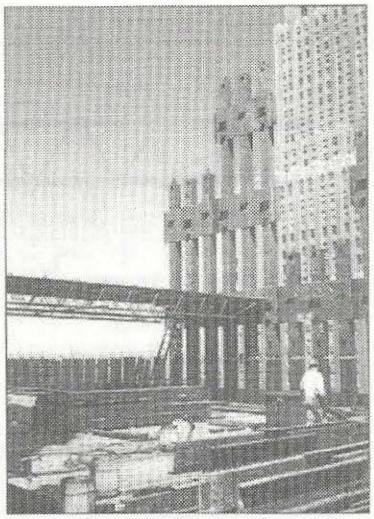
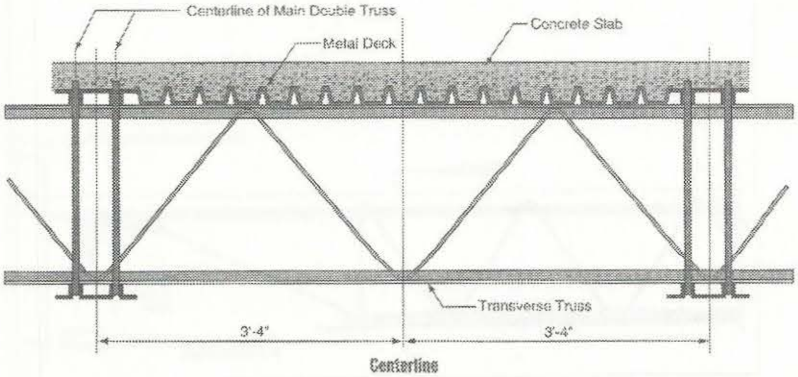


Figure 2-8 Erection of floor framing during original construction.



Centerline of Main Double Truss
Concrete Slab
Metal Deck
Transverse Truss
3'-4"
3'-4"
Centerline

Figure 2-9 Cross-section through main double trusses, showing transverse truss.

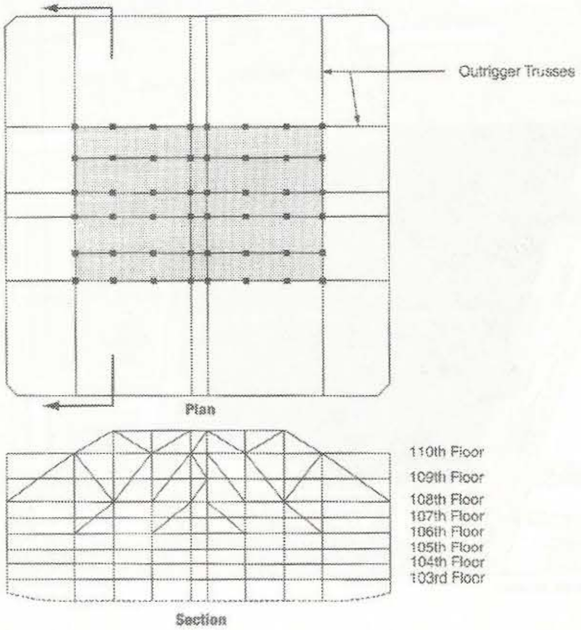


Figure 2-10 Outrigger truss system at tower roof.

4 extending across the short direction of the core. This outrigger truss system provided stiffening of the frame for wind resistance, mobilized some of the dead weight supported by the core to provide stability against wind-induced overturning, and also provided direct support for the transmission tower on WTC 1. Although WTC 2 did not have a transmission tower, the outrigger trusses in that building were also designed to support such a tower.

A deep subterranean structure was present beneath the WTC Plaza (Figure 2-11) and the two towers. The western half of this substructure, bounded by West Street to the west and by the 1/9 subway line that extends approximately between West Broadway and Greenwich Street on the east, was 70 feet deep and contained six subterranean levels. The structure housed a shopping mall and building mechanical and electrical services, and it also provided a station for the PATH subway line and parking for the complex.

Prior to construction, the site was underlain by deep deposits of fill material, informally placed over a period of several hundred years to displace the adjacent Hudson River shoreline and create additional usable land area. In order to construct this structure, the eventual perimeter walls for the subterranean structure were constructed using the slurry wall technique. After the concrete wall was cured and attained sufficient strength, excavation of the basement was initiated. As excavation proceeded downward, tieback anchors were drilled diagonally down through the wall and grouted into position in the rock deep behind the walls. These

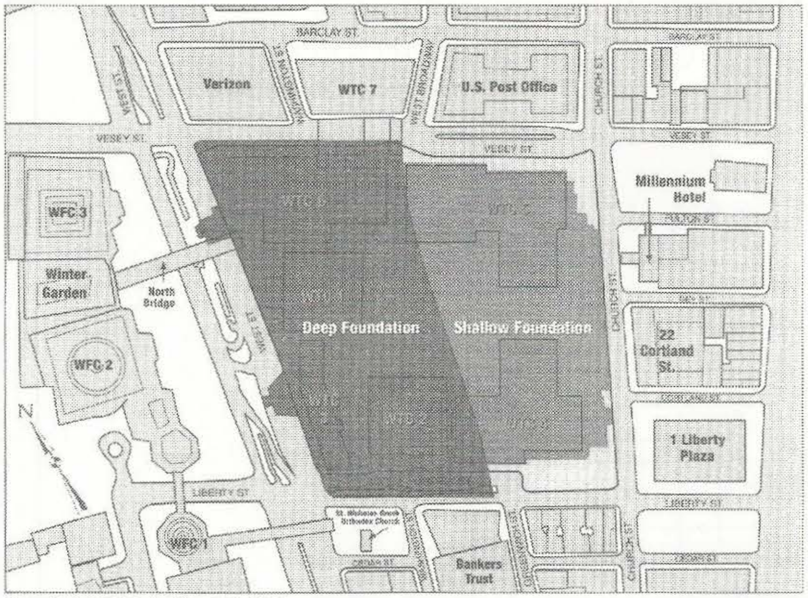

BARCLAY ST.
VESEY ST.
WEST ST.
WASHINGTON ST.
WEST BROADWAY
CHURCH ST.
FULTON ST.
LIBERTY ST.
Verizon
WTC 7
U.S. Post Office
Millennium Hotel
WFC 3
Winter Garden
North Bridge
Deep Foundation
Shallow Foundation
22 Cortland St.
WFC 2
1 Liberty Plaza
N
St. Nicholas Greek Orthodox Church
WFC 1
Bankers Trust

Figure 2-11 Location of subterranean structure.

anchors stabilized the wall against the soil and water pressures from the unexcavated side as the excavation continued on the inside. After the excavation was extended to the desired grade, foundations were formed and poured against the exposed bedrock, and the various subgrade levels of the structure were constructed.

Floors within the substructure were of reinforced concrete flat-slab construction, supported by structural steel columns. Many of these steel columns also provided support for the structures located above the plaza level. After the floor slabs were constructed, they were used to provide lateral support for the perimeter walls, holding back the earth pressure from the unexcavated side. The tiebacks, which had been installed as a temporary stabilizing measure, were decommissioned by cutting off their end anchorage hardware and repairing the pockets in the slurry wall where these anchors had existed.

Tower foundations beneath the substructure consisted of massive spread footings, socketed into and bearing directly on the massive bedrock. Steel grillages, consisting of layers of orthogonally placed steel beams, were used to transfer the immense column loads, in bearing, to the reinforced concrete footings.

2.1.3 Fire Protection

The fire safety of a building is provided by a system of interdependent fire protection features, including suppression systems, detection systems, notification devices, smoke management systems, and passive systems such as compartmentation and structural protection. The failure of any of these fire protection systems will impact the effectiveness of the other systems in the building.

2.1.3.1 Passive Protection

In WTC 1, structural elements up to the 39th floor were originally protected from fire with a spray-applied product containing asbestos (Nicholson, et al. 1980). These asbestos-containing materials were later abated inside the building, either through encapsulation or replacement. On all other floors and throughout WTC 2, a spray-applied, asbestos-free mineral fiber material was used. Each element of the steel floor trusses was protected with spray-applied material. The specific material used was a low-density, factory-mixed product consisting of manufactured inorganic fibers, proprietary cement-type binders, and other additives in low concentrations to promote wetting, set, and dust control. Air setting, hydraulic setting, and ceramic setting binders were added in varying quantities and combinations or singly at the site, depending on the particular application and weather conditions. Finally, water was added at the nozzle of the spray gun as the material was sprayed onto the member to be protected. The average thickness of spray-applied fireproofing on the trusses was 3/4 inch. In the mid-1990s, a decision was made to upgrade the fire protection by applying additional material onto the trusses so as to increase fireproofing thickness to 1-1/2 inches. The fireproofing upgrade was applied to individual floors as they became vacant. By September 11, 2001, a total of 31 stories had been upgraded, including the entire impact zone in WTC 1 (floors 94–98), but only the 78th floor in the impact zone in WTC 2 (floors 78–84).

Spandrels and girders were specified to have sufficient protection to achieve a 3-hour rating. Except for the interior face of perimeter columns between spandrels, which were protected with a plaster material, spray-applied materials similar to those used on the floor systems were used. The thickness of protection on spandrels and girders varied, with the more massive steel column sections receiving reduced fireproofing thickness relative to the thinner elements.

The primary vertical compartmentation was provided by the floor slabs that were cast flush against the spandrel beams at the exterior wall, providing separation between floors at the building perimeter. After a fire in 1975, vertical penetrations for cabling and plumbing were sealed with fire-resistant material. At stair and elevator shafts, separation was provided by a wall system constructed of metal studs and two layers of 5/8-inch thick gypsum board on the exterior and one layer of 5/8-inch thick gypsum board on the interior. These assemblies provided a 2-hour rating. Horizontal compartmentation varied throughout the complex. Some separating walls ran from slab to slab, while others extended only up to the suspended ceiling. A report by the New York Board of Fire Underwriters (NYBFU) titled *One World Trade Center Fire, February 13, 1975* (NYBFU 1975) presents a detailed discussion of the compartmentation features of the building at that time.

2.1.3.2 Suppression

When originally constructed, the two towers were not provided with automatic fire sprinkler protection. However, such protection was installed as a retrofit circa 1990, and automatic sprinklers covered nearly 100 percent of WTC 1 and WTC 2 at the time of the September 11 attacks. In addition, each building had standpipes running through each of its three stairways. A 1.5-inch hose line and a cabinet containing two air-pressurized water (APW) extinguishers were also present at each floor in each stairway.

The primary water supply was provided by a dedicated fire yard main that looped around most of the complex. This yard main was supplied directly from the municipal water supply. Two remotely located high-pressure, multi-stage, 750-gallons per minute (gpm) electrical fire pumps took suction from the New York City municipal water supply and produced the required operating pressures for the yard main.

Each tower had three electrical fire pumps that provided additional pressure for the standpipes. One pump, located on the 7th floor, received the discharge from the yard main fire pumps and moved it up to the 41st floor, where a second 750-gpm fire pump pushed it up to a third pump on the 75th floor. Each fire pump produced sufficient pressure to supply water to the pump two stages up from it in the event that any one pump should fail.

Several 5,000-gallon storage tanks, filled from the domestic water system, provided a secondary water supply. Tanks on the 41st, 75th, and 110th floors provided water directly to a standpipe system. A tank on the 20th floor supplied water directly to the yard main. Numerous Fire Department of New York (FDNY) connections were located around the complex to allow the fire department to boost water pressure in the buildings.

2.1.3.3 Smoke Management

A zoned smoke control system was built into each building's ventilation systems and was activated upon direction of the responding FDNY Incident Commander. The system was designed to limit smoke spread from the tenant areas to the core area, thereby assisting both individuals evacuating from an area and those responding to the scene by limiting smoke spread into the core.

2.1.3.4 Fire Department Features

At the time of the 1993 World Trade Center bombing, a centralized Fire Command Center (FCC) for the two towers was present at the Concourse level. This FCC was located in the B-1 level Operations Control Center (OCC). Following the 1993 bombing, additional FCCs were installed in the lobbies of each tower.

A Radiax cable and antenna were installed in the WTC complex to facilitate the use of FDNY radios in the towers. Fire department telephones were provided in both towers on odd floors in Stairway 3, as well as on levels B-1, B-4, and B-6.

The WTC had its own fire brigade, consisting of Port Authority police officers trained in fire safety, who worked with the FDNY to investigate fire conditions and take appropriate actions. The internal fire brigade had access to fire carts located on the Concourse level and on the 44th and 78th floor sky lobbies of each tower. These fire carts were equipped with hoses, nozzles, self-contained breathing apparatus, turnout coats, forcible entry tools, resuscitators, first-aid kits, and other emergency equipment. Typically, the WTC fire brigade would collect the nearest fire cart and set up operations on the floor below the fire floor.

The WTC complex had 24 Siamese connections located at street level for use by the FDNY apparatus. Each of these Siamese connections served various portions of the complex and was identified as such.

2.1.4 Emergency Egress

Each tower was provided with three independent emergency fire exit stairways, located in the core of the building, as indicated in Figure 2-12. Two of these stairways, designated Stairway 1 and Stairway 2, were 44 inches wide and ran to the 110th floor. The third stairway, designated Stairway 3, had a width of 56 inches and ran to the 108th floor. The stairways did not run in continuous vertical shafts from the top to the bottom of the structure. Instead, the plan location of the stairways shifted at some levels, and occupants traversing the stairways were required to move from one vertical shaft to another through a transfer corridor. Both Stairways 1 and 2 had transfers at the 42nd, 48th, 76th, and 82nd levels. Stairway 1 had an additional transfer at the 26th level and Stairway 3 had a single transfer at the 76th level. After the 1993 bombing, battery-operated emergency lighting was provided in the stairways and photoluminescent paint was placed on the edge of the stair treads to facilitate emergency egress.

There were 99 elevators in each of the two towers, including 23 express elevators; however, the express elevators were not intended to be used for emergency access or egress. There were also several freight elevators servicing groups of floors in the buildings. The several elevators that served each floor were broken into two groups that operated on different power supplies.

Upon alarm activation, an automatic elevator override system commanded all elevators serving or affected by a fire area to immediately return to the ground floor, or to their sky lobby (44th and 78th floors). From there, the elevators could be operated manually by the FDNY. Although many fire departments

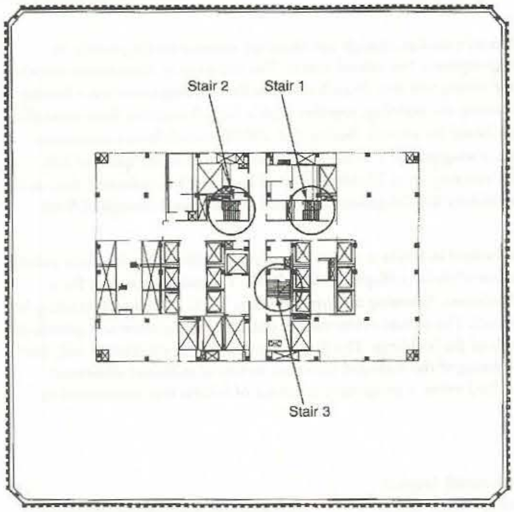


Figure 2-12
Floor plan of 94th and 95th floors of WTC 1 showing egress stairways.

routinely use elevators to provide better access in high-rise buildings, FDNY does not do this, because there have been fatalities associated with such use.

2.1.5 Emergency Power

Primary power was provided at 13.8 kilovolts (kV) through a ground level substation in WTC 7 near the Barclay Street entrance to the underground parking garage. The primary power was wired to the buildings through two separate systems. The first provided power throughout each building; the second provided power to emergency systems in the event that the primary wiring system failed.

Six 1,200-kilowatt (kW) emergency power generators located in the sixth basement (B-6) level provided a secondary power supply. These generators were checked on a routine basis to ensure that they would function properly during an emergency. This equipment provided backup power for communications equipment, elevators, emergency lighting in corridors and stairwells, and fire pumps. Telephone systems were provided with an independent battery backup system. Emergency lighting units in exit stairways, elevator lobbies, and elevator cabs were equipped with individual backup batteries.

2.1.6 Management Procedures

The Port Authority has a risk management group that coordinates fire and safety activities for their various properties. This group provided training for the WTC fire brigade, fire safety directors, and tenant fire wardens. The WTC had 25 fire safety directors who assisted in the coordination of fire safety activities in the buildings throughout the year. Six satellite communication stations, staffed by deputy fire safety directors, were spaced throughout the towers. In addition, each tenant was required to provide at least one fire warden. Tenants that occupied large areas of the building were required to provide one fire warden for every 7,500 square feet of occupied space. The fire safety directors trained the fire wardens and fire drills were held twice a year.

2.2 Building Response

WTC 1 and WTC 2 each experienced a similar, though not identical, series of loading events. In essence, each tower was subjected to three separate, but related events. The sequence of these events was the same for the two buildings, although the timing was not. In each case, the first loading event was a Boeing 767-200ER series commercial aircraft hitting the building, together with a fireball resulting from immediate rapid ignition of a portion of the fuel on board the aircraft. Boeing 767-200ER aircraft have a maximum rated takeoff weight of 395,000 pounds, a wingspan of 156 feet 1 inch, and a rated cruise speed of 530 miles per hour. The aircraft is capable of carrying up to 23,980 gallons of fuel, and it is estimated that, at the time of impact, each aircraft had approximately 10,000 gallons of unused fuel on board (compiled from Government sources).

In each case, the aircraft impacts resulted in severe structural damage, including some localized partial collapse, but did not result in the initiation of global collapse. In fact, WTC 1 remained standing for a period of approximately 1 hour and 43 minutes, following the initial impact; WTC 2 remained standing for approximately 56 minutes following impact. The second event was the simultaneous ignition and growth of fires over large floor areas on several levels of the buildings. The fires heated the structural systems and, over a period of time, resulted in additional stressing of the damaged structure, as well as sufficient additional damage and strength loss to initiate the third event, a progressive sequence of failures that culminated in total collapse of both structures.

2.2.1 WTC 1

2.2.1.1 Initial Damage From Aircraft Impact

American Airlines Flight 11 struck the north face of WTC 1 approximately between the 94th and 98th floors (Figures 2-13 and 2-14), causing massive damage to the north face of the building within the immediate area (Figure 2-15). At the central zone of impact corresponding to the airplane fuselage and engines, at least five of the prefabricated, three-column sections that formed the exterior walls were broken loose of the structure, and some were pushed inside the building envelope. Locally, floors supported by these exterior wall sections appear to have partially collapsed, losing their support along the exterior wall. Away from this central zone, in areas impacted by the outer wing structures, the exterior columns were fractured by the force of the collision. Interpretation of photographic evidence suggests that from 31 to 36 columns on the north building face were destroyed over portions of a four-story range. Partial collapse of floors in this zone appear to have occurred over a horizontal length of wall of approximately 65 feet, while floors in other portions of the building appear to have remained intact. Figure 2-16 shows the damage to the exterior columns on the impacted face of WTC 1.

In addition to this damage at the building perimeter, a significant but undefined amount of damage also occurred to framing at the central core. Interviews were conducted with persons who were present in offices on the 91st floor of the building at the north face of the structure, three floors below the approximate zone of impact. Their descriptions of the damage evident at this floor level immediately following the aircraft impact suggest relatively slight damage at the exterior wall of the building, but progressively greater damage to the south and east. They described extensive building debris in the eastern portion of the central core, preventing their access to the easternmost exit stairway. This suggests the possibility of immediate partial collapse of framing in the central core. These persons also described the presence of debris from collapsed partition walls from upper floors in stairways located further to the west, suggesting the possibility of some structural damage in the northwestern portion of the core framing as well. Figure 2-17 is a sketch made during an interview with building occupants indicating portions of the 91st floor that could not be accessed due to accumulated debris.

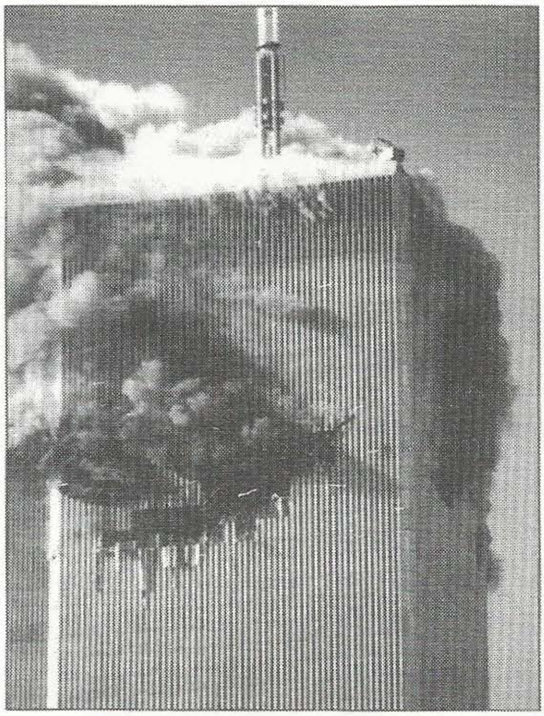


Figure 2-13 Zone of aircraft impact on the north face of WTC 1.

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It is known that some debris from the aircraft traveled completely through the structure. For example, life jackets and portions of seats from the aircraft were found on the roof of the Bankers Trust building, located to the south of WTC 2. Part of the landing gear from this aircraft was found at the corner of West and Rector Streets, some five blocks south of the WTC complex (Figure 2-18). As this debris passed through the building, it doubtless caused some level of damage to the structure across the floor plate, including, potentially, interior framing, core columns, framing at the east, south, and west walls, and the floors themselves. The exact extent of this damage will likely never be known with certainty. It is evident that, despite this damage, the structure retained sufficient integrity and strength to remain globally stable for a period of approximately 1 hour and 43 minutes.

The building's structural system, composed of the exterior loadbearing frame, the gravity loadbearing frame at the central core, and the system of deep outrigger trusses in upper stories, was highly redundant. This permitted the building to limit the immediate zone of collapse to the area where several stories of exterior columns were destroyed by the initial impact and, perhaps, to portions of the central core as

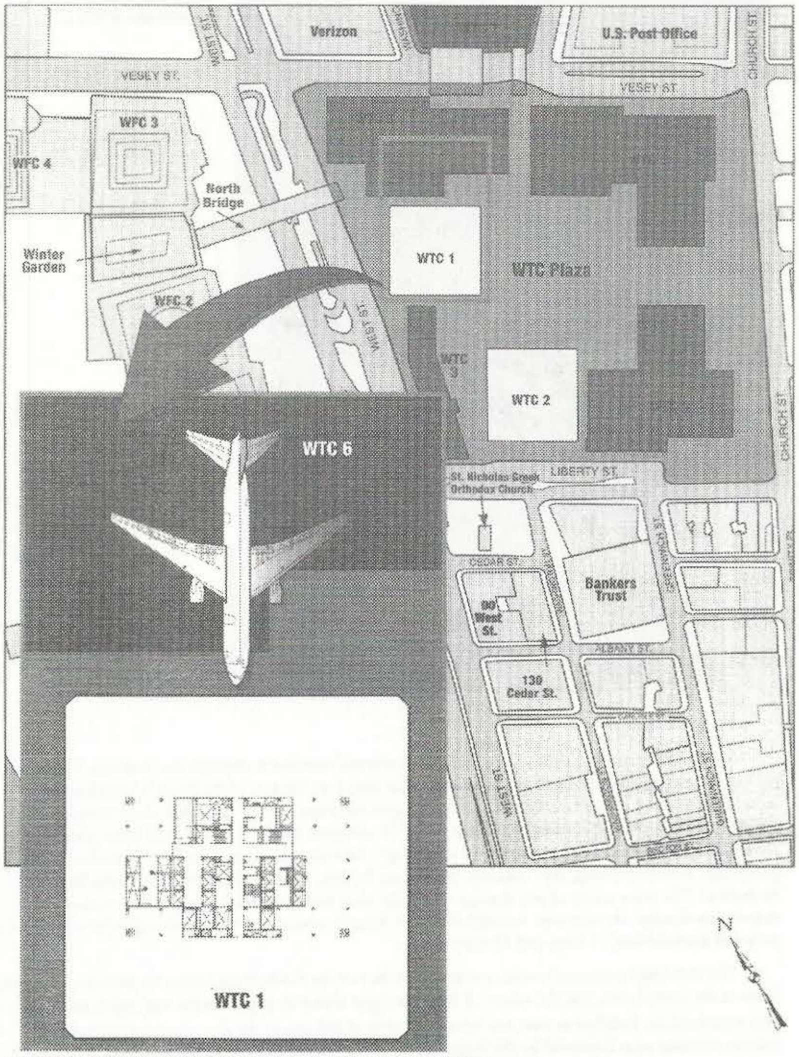
Verizon
U.S. Post Office
VESEY ST.
VESEY ST.
WEST ST.
CHURCH ST.
WFC 3
WFC 4
North Bridge
Winter Garden
WFC 2
WTC 1
WTC Plaza
WEST ST.
WTC 3
WTC 2
WTC 6
CHURCH ST.
LIBERTY ST.
St. Nicholas Greek Orthodox Church
CEDAR ST.
Bankers Trust
GREENWICH ST.
90 West St.
ALBANY ST.
130 Cedar St.
WEST ST.
WTC 1
N

Figure 2-14 Approximate zone of impact of aircraft on the north face of WTC 1.

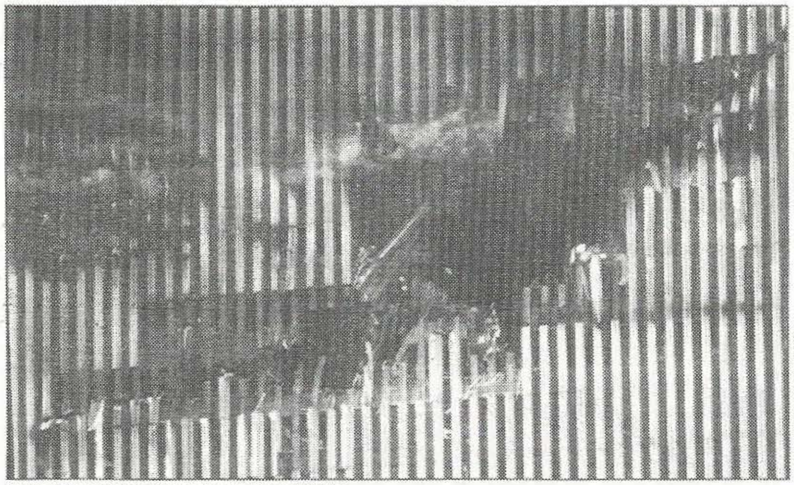

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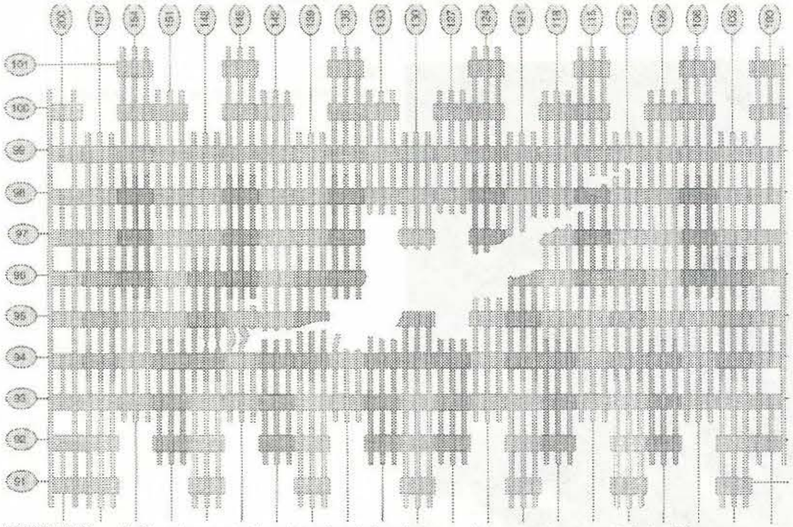
Figure 2-15 Impact damage to the north face of WTC 1.


160
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92
91

GENERAL NOTES: (1) Column damage captured from photographs and enhanced videos. (2) Damage to column lines 111-115 at level 98 is estimated.

Figure 2-16 Impact damage to exterior columns on the north face of WTC 1.

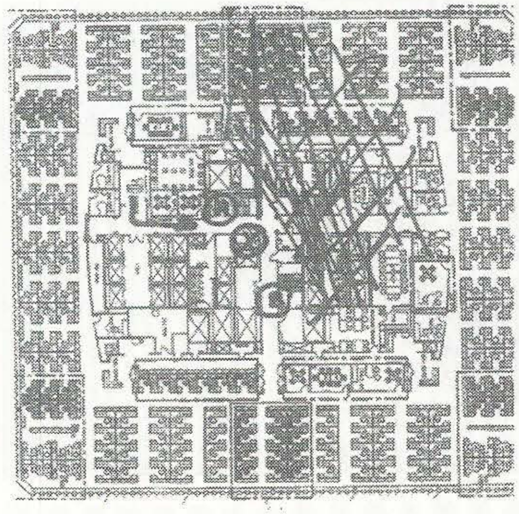


Figure 2-17
Approximate debris location on the 91st floor of WTC 1.

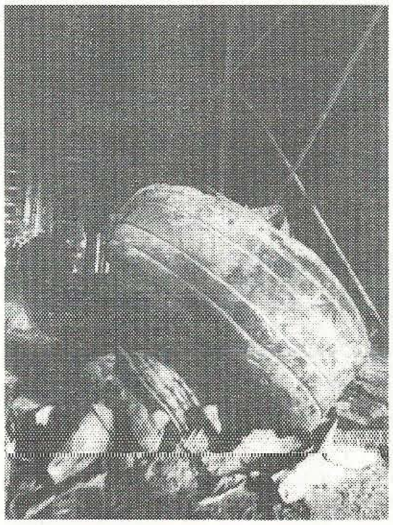


Figure 2-18
Landing gear found at the corner of West and Rector Streets.

previously described. Following the impact, floor loads originally supported by the exterior columns in compression were successfully transferred to other load paths. Most of the load supported by the failed columns is believed to have transferred to adjacent perimeter columns through Vierendeel behavior of the exterior wall frame. Preliminary structural analyses of similar damage to WTC 2 suggests that axial load demands on columns immediately adjacent to the destroyed columns may have increased by as much as a factor of 6 relative to the load state prior to aircraft impact. However, these exterior columns appear to have had substantial overstrength for gravity loads.

Neglecting the potential loss of lateral support resulting from collapsed floor slabs and any loss of strength due to elevated temperatures from fires, the most heavily loaded columns were probably near, but not over, their ultimate capacities. Columns located further from the impact zone are thought to have remained substantially below their ultimate capacities. The preliminary analyses also indicate that loss of the columns resulted in some immediate tilting of the structure toward the impact area, subjecting the remaining columns and structure to additional stresses from P-delta effects. Also, in part, exterior columns above the zone of impact were converted from compression members to hanger-type tension members, so that, in effect, a portion of the floors' weight became suspended from the outrigger trusses (Figure 2-10) and were transferred back to the interior core columns. The outrigger trusses also would have been capable of transferring some of the load carried by damaged core columns to adjacent core columns. Figure 2-19 illustrates these various secondary load paths. Section 2.2.2.2 provides a more detailed description of these analyses and findings.

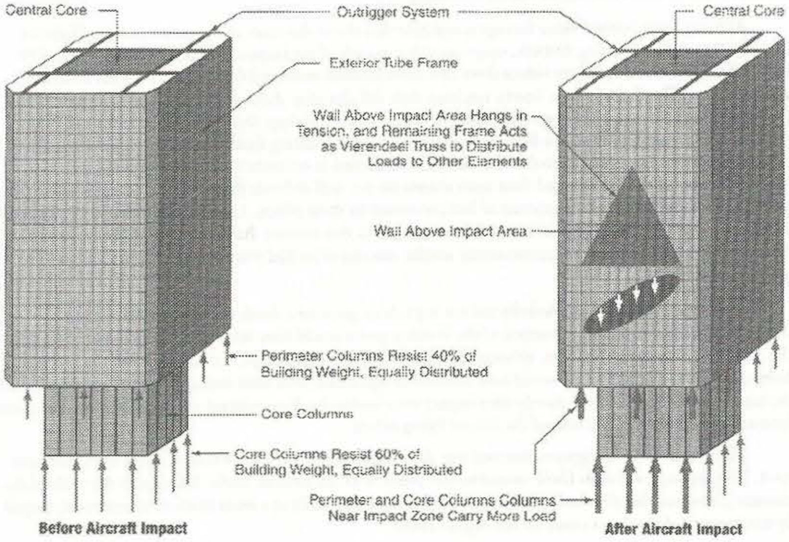

Central Core
Outrigger System
Central Core
Exterior Tube Frame
Wall Above Impact Area Hangs in Tension, and Remaining Frame Acts as Vierendeel Truss to Distribute Loads to Other Elements
Wall Above Impact Area
Perimeter Columns Resist 40% of Building Weight, Equally Distributed
Core Columns
Core Columns Resist 60% of Building Weight, Equally Distributed
Perimeter and Core Columns Columns Near Impact Zone Carry More Load
Before Aircraft Impact
After Aircraft Impact

Figure 2-19 Redistribution of load after aircraft impact.

Following the aircraft impact into the building, the structure was able to successfully redistribute the building weight to the remaining elements and to maintain a stable condition. This return to a stable condition is suggested by the preliminary analyses and also evidenced by the fact that the structure remained standing for 1 hour and 43 minutes following the impact. However, the structure's global strength was severely degraded. Although the structure may have been able to remain standing in this weakened condition for an indefinite period, it had limited ability to resist additional loading and could potentially have collapsed as a result of any severe loading event, such as that produced by high winds or earthquakes. WTC 1 probably experienced some additional loading and damage due to the collapse of the adjacent WTC 2. The extent of such damage is not known but likely included broken window and façade elements along the south face. This additional damage was not sufficient to cause collapse. The first event of sufficient severity to cause collapse was the fires that followed the aircraft impact.

2.2.1.2 Fire Development

It is estimated, based on information compiled from Government sources, that each aircraft contained about 10,000 gallons of jet fuel upon impact into the buildings. A review of photographic and video records show that the aircraft fully entered the buildings prior to any visual evidence of flames at the exteriors of the buildings. This suggests that, as the aircraft crashed into and plowed across the buildings, they distributed jet fuel throughout the impact area to form a flammable "cloud." Ignition of this cloud resulted in a rapid pressure rise, expelling a fuel rich mixture from the impact area into shafts and through other openings caused by the crashes, resulting in dramatic fireballs.

Although only limited video footage is available that shows the crash of American Airlines Flight 11 into WTC 1 and the ensuing fireballs, extensive video records of the impact of United Airlines Flight 175 into WTC 2 are available. These videos show that three fireballs emanated from WTC 2 on the south, east, and west faces. The fireballs grew slowly, reaching their full size after about 2 seconds. The diameters of the fireballs were greater than 200 feet, exceeding the width of the building. Such fireballs were formed when the expelled jet fuel dispersed and flames traveled through the resulting fuel/air mixture. Experimentally based correlations for similar fireballs (Zalosh 1995) were used to estimate the amount of fuel consumed. The precise size of the fireballs and their exact shapes are not well defined; therefore, there is some uncertainty associated with estimates of the amount of fuel consumed by these effects. Calculations indicate that between 1,000 and 3,000 gallons of jet fuel were likely consumed in this manner. Barring additional information, it is reasonable to assume that an approximately similar amount of jet fuel was consumed by fireballs as the aircraft struck WTC 1.

Although dramatic, these fireballs did not explode or generate a shock wave. If an explosion or detonation had occurred, the expansion of the burning gasses would have taken place in microseconds, not the 2 seconds observed. Therefore, although there were some overpressures, it is unlikely that the fireballs, being external to the buildings, would have resulted in significant structural damage. It is not known whether the windows that were broken shortly after impact were broken by these external overpressures, overpressures internal to the building, the heat of the fire, or flying debris.

The first arriving firefighters observed that the windows of WTC 1 were broken out at the Concourse level. This breakage was most likely caused by overpressure in the elevator shafts. Damage to the walls of the elevator shafts was also observed as low as the 23rd floor, presumably as a result of the overpressures developed by the burning of the vapor cloud on the impact floors.

If one assumes that approximately 3,000 gallons of fuel were consumed in the initial fireballs, then the remainder either escaped the impact floors in the manners described above or was consumed by the fire on the impact floors. If half flowed away, then approximately 4,000 gallons remained on the impact floors to be consumed in the fires that followed. The jet fuel in the aerosol would have burned out as fast as the flame could spread through it, igniting almost every combustible on the floors involved. Fuel that fell to the floor and did not flow out of the building would have burned as a pool or spill fire at the point where it came to rest.

The time to consume the jet fuel can be reasonably computed. At the upper bound, if one assumes that all 10,000 gallons of fuel were evenly spread across a single building floor, it would form a pool that would be consumed by fire in less than 5 minutes (SFPE 1995) provided sufficient air for combustion was available. In reality, the jet fuel would have been distributed over multiple floors, and some would have been transported to other locations. Some would have been absorbed by carpeting or other furnishings, consumed in the flash fire in the aerosol, expelled and consumed externally in the fireballs, or flowed away from the fire floors. Accounting for these factors, it is believed that almost all of the jet fuel that remained on the impact floors was consumed in the first few minutes of the fire.

As the jet fuel burned, the resulting heat ignited office contents throughout a major portion of several of the impact floors, as well as combustible material within the aircraft itself.

A limited amount of physical evidence about the fires is available in the form of videos and still photographs of the buildings and the smoke plume generated soon after the initial attack. Estimates of the buoyant energy in the plume were obtained by plotting the rise of the smoke plume, which is governed by buoyancy in the vertical direction and by the wind in the horizontal direction. Using the Computational Fluid Dynamics (CFD) fire model, Fire Dynamics Simulator Ver. 1 (FDS1), fire scientists at the National Institute of Standards and Technology (NIST) (Rehm, et al. 2002) were able to mathematically approximate the size of fires required to produce such a smoke plume. As input to this model, an estimate of the openings available to provide ventilation for the fires was obtained from an examination of photographs taken of the damaged tower. Meteorological data on wind velocity and atmospheric temperatures were provided by the National Oceanic and Atmospheric Administration (NOAA) based on reports from the Aircraft Communications Addressing and Reporting System (ACARS). The information used weather monitoring instruments onboard three aircraft that departed from LaGuardia and Newark airports between 7:15 a.m. and 9:00 a.m. on September 11, 2001. The wind speed at heights equal to the upper stories of the towers was in the range of 10–20 mph. The outside temperatures over the height of the building were 20–21 °C (68–70 °F).

The modeling suggests a peak total rate of fire energy output on the order of 3–5 trillion Btu/hr, around 1–1.5 gigawatts (GW), for each of the two towers. From one third to one half of this energy flowed out of the structures. This vented energy was the force that drove the external smoke plume. The vented energy and accompanying smoke from both towers combined into a single plume. The energy output from each of the two buildings is similar to the power output of a commercial power generating station. The modeling also suggests ceiling gas temperatures of 1,000 °C (1,800 °F), with an estimated confidence of plus or minus 100 °C (200 °F) or about 900–1,100 °C (1,600–2,000 °F). A major portion of the uncertainty in these estimates is due to the scarcity of data regarding the initial conditions within the building and how the aircraft impact changed the geometry and fuel loading. Temperatures may have been as high as 900–1,100 °C (1,700–2,000 °F) in some areas and 400–800 °C (800–1,500 °F) in others.

The viability of a 3–5 trillion Btu/hr (1–1.15 GW) fire depends on the fuel and air supply. The surface area of office contents needed to support such a fire ranges from about 30,000–50,000 square feet, depending on the composition and final arrangement of the contents and the fuel loading present. Given the typical occupied area of a floor as approximately 30,000 square feet, it can be seen that simultaneous fire involvement of an area equal to 1–2 entire floors can produce such a fire. Fuel loads are typically described in terms of the equivalent weight of wood. Fuel loads in office-type occupancies typically range from about 4–12 psf, with the mean slightly less than 8 psf (Culver 1977). File rooms, libraries, and similar concentrations of paper materials have significantly higher concentrations of fuel. At the burning rate necessary to yield these fires, a fuel load of about 5 psf would be required to provide sufficient fuel to maintain the fire at full force for an hour, and twice that quantity to maintain it for 2 hours. The air needed to support combustion would be on the order of 600,000–1,000,000 cubic feet per minute.

Air supply to support the fires was primarily provided by openings in the exterior walls that were created by the aircraft impacts and fireballs, as well as by additional window breakage from the ensuing heat of the fires. Table 2.1 lists the estimated exterior wall openings used in these calculations. Although the table shows the openings on a floor-by-floor basis, several of the openings, particularly in the area of impact, actually spanned several floors (see Figure 2-17).

Sometimes, interior shafts in burning high-rise buildings also deliver significant quantities of air to a fire, through a phenomenon known as "stack effect," which is created when differences between the ambient exterior air temperatures and the air temperatures inside the building result in differential air pressures, drawing air up through the shafts to the fire area. Because outside and inside temperatures appear to have been virtually the same on September 11, this stack effect was not expected to be strong in this case.

Based on photographic evidence, the fire burned as a distributed collection of large but separate fires with significant temperature variations from space to space, depending on the type and arrangement of combustible material present and the available air for combustion in each particular space. Consequently, the temperature and related incident heat flux to the structural elements varied with both time and location. This information is not currently available, but could be modeled with advanced CFD fire models.

Damage caused by the aircraft impacts is believed to have disrupted the sprinkler and fire standpipe systems, preventing effective operation of either the manual or automatic suppression systems. Even if these systems had not been compromised by the impacts, they would likely have been ineffective. It is believed that the initial flash fires of jet fuel would have opened so many sprinkler heads that the systems would have quickly depressurized and been unable to effectively deliver water to the large area of fire involvement. Further, the initial spread of fires was so extensive as to make occupant use of small hose streams ineffective.

Table 2.1 Estimated Openings in Exterior Walls of WTC 1

Floor	North Wall		South Wall		East Wall		West Wall		Total Area	
	ft^2	(m^2)	ft^2	(m^2)	ft^2	(m^2)	ft^2	(m^2)	ft^2	(m^2)
92	743	(69)	0	(0)	1,572	(146)	0	(0)	2,314	(215)
93	958	(89)	0	(0)	1,356	(126)	0	(0)	2,314	(215)
94	592	(55)	54	(5)	1,163	(108)	0	(0)	1,808	(168)
95	1,055	(98)	54	(5)	0	(0)	420	(39)	1,528	(142)
96	797	(74)	151	(14)	0	(0)	1,518	(141)	2,465	(229)
97	926	(86)	151	(14)	0	(0)	1,798	(167)	2,874	(267)
98	1,335	(124)	0	(0)	0	(0)	0	(0)	1,335	(124)
TOTAL	6,405	(595)	409	(38)	4,090	(380)	3,735	(347)	14,639	(1,360)

NOTE: Differences in totals are due to rounding in the conversion of square meters to square feet.

2.2.1.3 Evacuation

Some occupants of WTC 1 and WTC 2 began to voluntarily evacuate the buildings soon after the first aircraft struck WTC 1. Full evacuation of all occupants below the impact floors in WTC 1 was ordered soon after the second plane hit the south tower (Smith 2002). As indicated by Cauchon (2001a), the overall evacuation of the towers was as much of a success as thought possible, given the overall incident. Cauchon indicates that, between both towers, 99 percent of the people below the floors of impact survived (2001a) and by the time WTC 2 collapsed, the stairways in WTC 1 were observed to be virtually clear of building occupants (Smith 2002). In part this was possible because conditions in the stairways below the impact levels largely remained tenable. However, this may also be a result of physical changes and training programs put into place following the 1993 WTC bombing. Important modifications to building egress made following the 1993 WTC bombing included the placement of photo-luminescent paint on the egress paths to assist in wayfinding (particularly at the stair transfer corridors) and provision of emergency lighting for the stairways. In addition, an evacuation training program was instituted (Masetti 2001).

Shortly before the times of collapse, the stairways were reported as being relatively clear, indicating that occupants who were physically capable and had access to egress routes were able to evacuate from the buildings (Mayblum 2001). People within and above the impact area could not evacuate, simply because the stairways in the impact area had been destroyed.

Some survivors reported that, at about the same time that WTC 2 collapsed, lighting in the stairways of WTC 1 was lost (Mayblum 2001). Also, there were several accounts of water flowing down the stairways and of stairwells becoming slippery beginning at the 10th floor (Labriola 2001).

Anecdotes indicate altruistic behavior was commonly displayed. Some mobility-impaired occupants were carried down many flights of stairs by other occupants. There were also reports of people frequently stepping aside and temporarily stopping their evacuation to let burned and badly injured occupants pass by (Dateline NBC 2001, Hearst 2001). Occupants evacuating from the 91st floor noted that, as they descended to lower levels of the building, traffic was considerably impaired and formed into a slowly moving single-file progression, as evacuees worked their way around firefighters and other emergency responders, who were working their way up the stairways or who were resting from the exertion of the climb (Shark and McIntyre 2001).

2.2.1.4 Structural Response to Fire Loading

As previously indicated, the impact of the aircraft into WTC 1 substantially degraded the strength of the structure to withstand additional loading and also made the building more susceptible to fire-induced failure. Among the most significant factors:

- The force of the impact and the resulting debris field and fireballs probably compromised spray-applied fire protection of some steel members in the immediate area of impact. The exact extent of this damage will probably never be known, but this likely resulted in greater susceptibility of the structure to fire-related failure.
- Some of the columns were under elevated states of stress following the impact, due to the transfer of load from the destroyed and damaged elements.
- Some portions of floor framing directly beneath the partially collapsed areas were carrying substantial additional weight from the resulting debris and, in some cases, were likely carrying greater loads than they were designed to resist.

As fire spread and raised the temperature of structural members, the structure was further stressed and weakened, until it eventually was unable to support its immense weight. Although the specific chain of events that led to the eventual collapse will probably never be identified, the following effects of fire on structures may each have contributed to the collapse in some way. Appendix A presents a more detailed discussion of the structural effects of fire.

- As floor framing and supported slabs above and in a fire area are heated, they expand. As a structure expands, it can develop additional, potentially large, stresses in some elements. If the resulting stress state exceeds the capacity of some members or their connections, this can initiate a series of failures (Figure 2-20).
- As the temperature of floor slabs and support framing increases, these elements can lose rigidity and sag into catenary action. As catenary action progresses, horizontal framing elements and floor slabs become tensile elements, which can cause failure of end connections (Figure 2-21) and allow supported floors to collapse onto the floors below. The presence of large amounts of debris on some floors of WTC 1 would have made them even more susceptible to this behavior. In addition to overloading the floors below, and potentially resulting in a pancake-type collapse of successive floors, local floor collapse would also immediately increase the laterally unsupported length of columns, permitting buckling to begin. As indicated in Appendix B, the propensity of exterior columns to buckle would have been governed by the relatively weak bolted column splices between the vertically stacked prefabricated exterior wall units. This effect would be even more likely to occur in a fire that involves several adjacent floor levels simultaneously, because the columns could effectively lose lateral support over several stories (Figure 2-22).
- As the temperature of column steel increases, the yield strength and modulus of elasticity degrade and the critical buckling strength of the columns will decrease, potentially initiating buckling, even if lateral support is maintained. This effect is most likely to have been significant in the failure of the interior core columns.

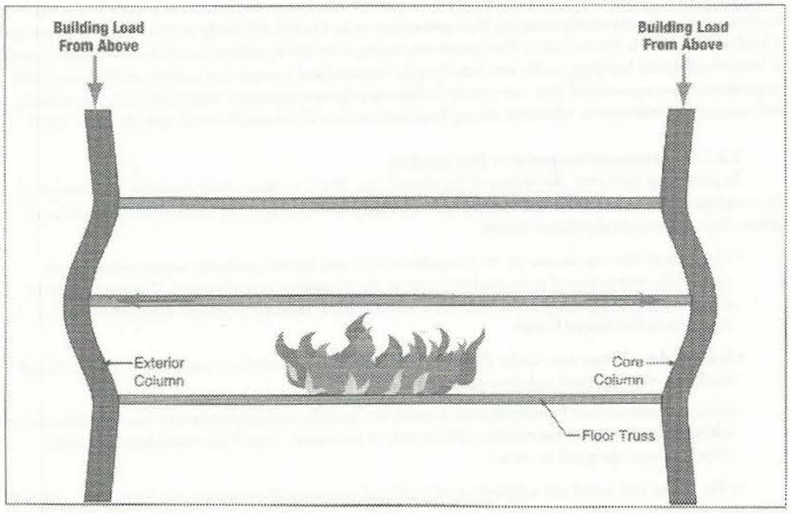


Figure 2-20 Expansion of floor slabs and framing results in outward deflection of columns and potential overload.

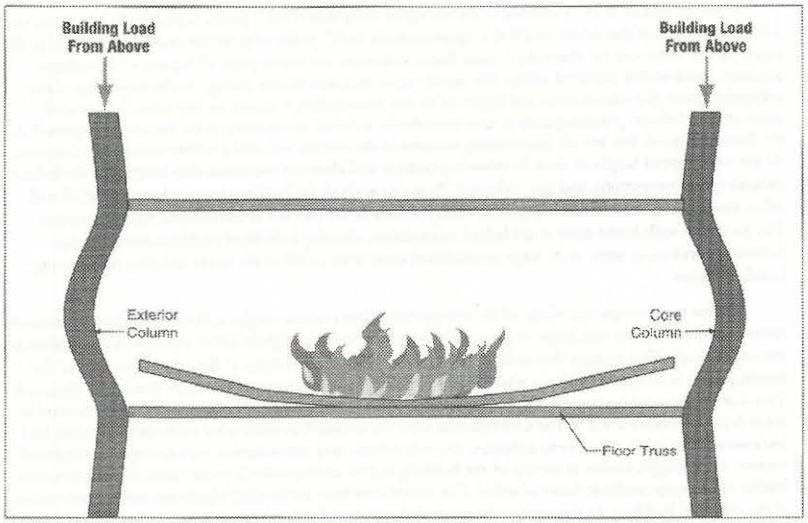

Building Load From Above
Building Load From Above
Exterior Column
Core Column
Floor Truss

Figure 2-21 Buckling of columns initiated by failure of floor framing and connections.

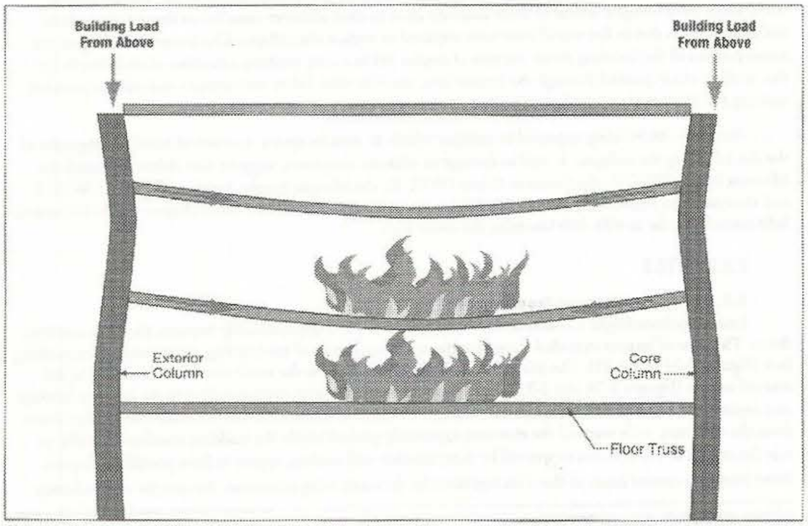

Building Load From Above
Building Load From Above
Exterior Column
Core Column
Floor Truss

Figure 2-22 Catenary action of floor framing on several floors initiates column buckling failures.

2.2.1.5 Progression of Collapse

Construction of WTC 1 resulted in the storage of more than 4×10^{11} joules of potential energy over the 1,368-foot height of the structure. Of this, approximately 8×10^{9} joules of potential energy were stored in the upper part of the structure, above the impact floors, relative to the lowest point of impact. Once collapse initiated, much of this potential energy was rapidly converted into kinetic energy. As the large mass of the collapsing floors above accelerated and impacted on the floors below, it caused an immediate progressive series of floor failures, punching each in turn onto the floor below, accelerating as the sequence progressed. As the floors collapsed, this left tall freestanding portions of the exterior wall and possibly central core columns. As the unsupported height of these freestanding exterior wall elements increased, they buckled at the bolted column splice connections, and also collapsed. Perimeter walls of the building seem to have peeled off and fallen directly away from the building face, while portions of the core fell in a somewhat random manner. The perimeter walls broke apart at the bolted connections, allowing individual prefabricated units that formed the wall or, in some cases, large assemblies of these units to fall to the street and onto neighboring buildings below.

Review of videotape recordings of the collapse taken from various angles indicates that the transmission tower on top of the structure began to move downward and laterally slightly before movement was evident at the exterior wall. This suggests that collapse began with one or more failures in the central core area of the building. This is consistent with the observations of debris patterns from the 91st floor, previously discussed. This is also supported by preliminary evaluation of the load carrying capacity of these columns, discussed in more detail in Section 2.2.2.2. The core columns were not designed to resist wind loads and, therefore, had less reserve capacity than perimeter columns. As some exterior and core columns were damaged by the aircraft impact, the outrigger trusses at the top of the building shifted additional loads to the remaining core columns, further eroding the available factor of safety. This would have been particularly significant in the upper portion of the damaged building. In this region, the original design load for the core columns was less than at lower floors, and the column sections were relatively light. The increased stresses caused by the aircraft impact could easily have brought several of these columns close to their ultimate capacity, so that relatively little additional effects due to fire would have been required to initiate the collapse. Once movement began, the entire portion of the building above the area of impact fell in a unit, pushing a cushion of air below it. As this cushion of air pushed through the impact area, the fires were fed by new oxygen and pushed outward, creating the illusion of a secondary explosion.

Although the building appeared to collapse within its own footprint, a review of aerial photographs of the site following the collapse, as well as damage to adjacent structures, suggests that debris impacted the Marriott Hotel (WTC 3), the Customs House (WTC 6), the Morgan Stanley building (WTC 5), WTC 7, and the American Express and Winter Garden buildings located across West Street (Figure 2-23). The debris field extended as far as 400–500 feet from the tower base.

2.2.2 WTC 2

2.2.2.1 Initial Damage From Aircraft Impact

United Airlines Flight 175 struck the south face of WTC 2 approximately between the 78th and 84th floors. The zone of impact extended from near the southeast corner of the building across much of the building face (Figures 2-24 and 2-25). The aircraft caused massive damage to the south face of the building in the zone of impact (Figures 2-26 and 2-27). At the central zone of impact corresponding to the airplane fuselage and engines, six of the prefabricated, three-column sections that formed the exterior walls were broken loose from the structure, with some of the elements apparently pushed inside the building envelope. Locally, as was the case in WTC 1, floors supported by these exterior wall sections appear to have partially collapsed. Away from this central zone, in the areas impacted by the outer wing structures, the exterior steel columns

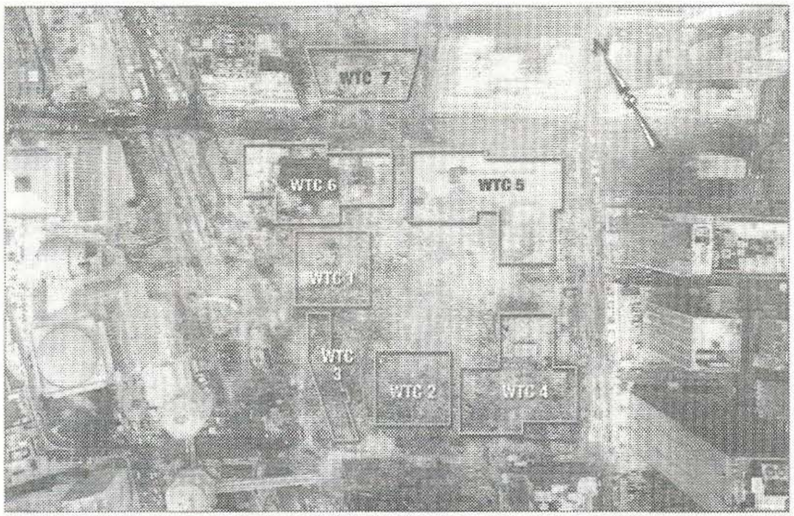

N
WTC 7
WTC 6
WTC 5
WTC 1
WTC 3
WTC 2
WTC 4

Figure 2-23 Aerial photograph of the WTC site after September 11 attack showing adjacent buildings damaged by debris from the collapse of WTC 1.

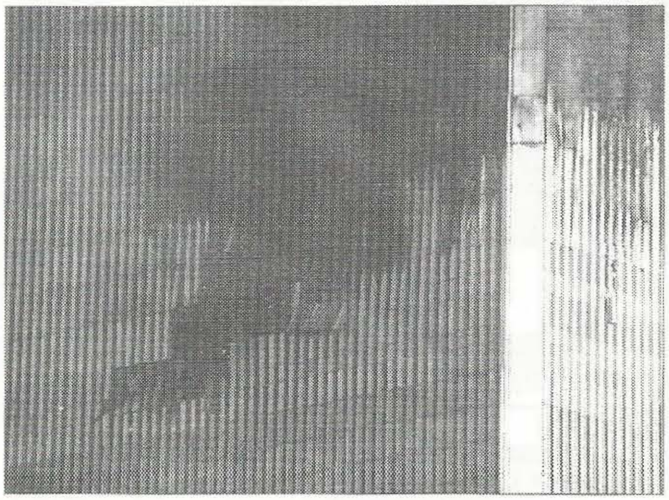
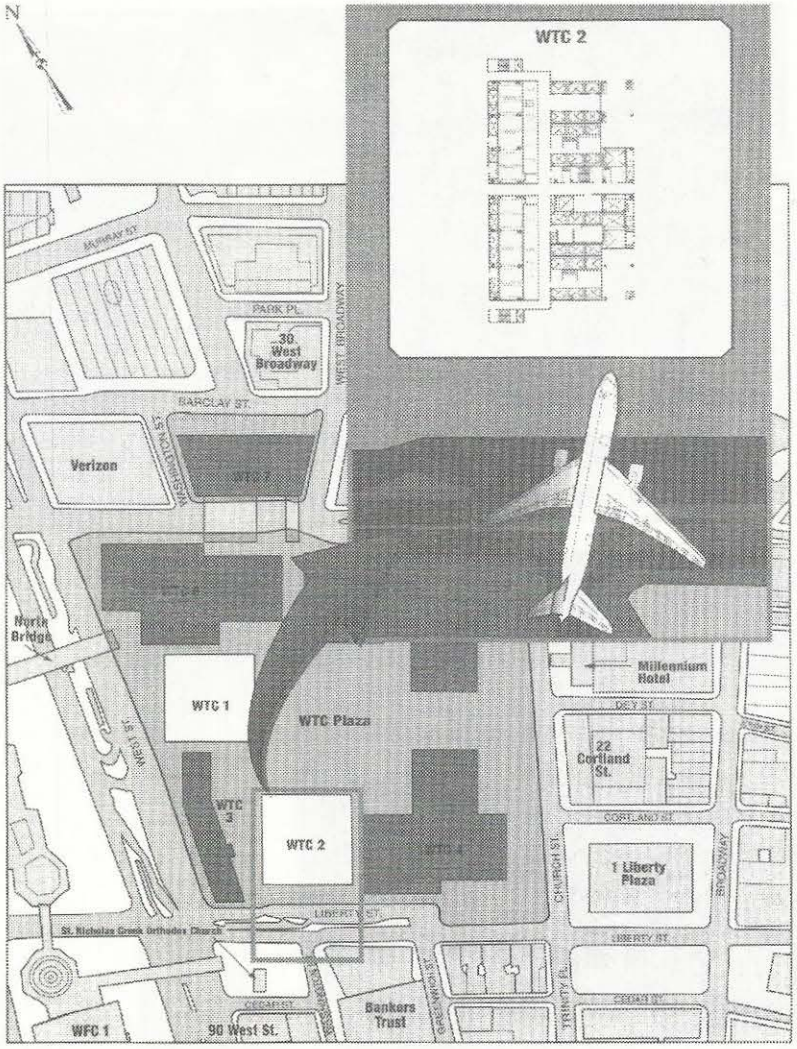


Figure 2-24 Southeast corner of WTC 2 shortly after aircraft impact.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WTC 2
MURRAY ST
PARK PL.
30 West Broadway
WEST BROADWAY
BARCLAY ST.
Verizon
WASHINGTON ST
WTC 7
WTC 6
North Bridge
WTC 1
WTC Plaza
WEST ST.
WTC 3
WTC 2
WTC 4
Millennium Hotel
DEY ST
22 Cortland St.
CORTLAND ST
CHURCH ST
1 Liberty Plaza
BROADWAY
LIBERTY ST.
St. Nicholas Greek Orthodox Church
LIBERTY ST
CEDAR ST.
WASHINGTON ST
GREENWICH ST
TRINITY PL.
CEDAR ST.
Bankers Trust
WFC 1
90 West St.

Figure 2-25 Approximate zone of impact of aircraft on the south face of WTC 2.

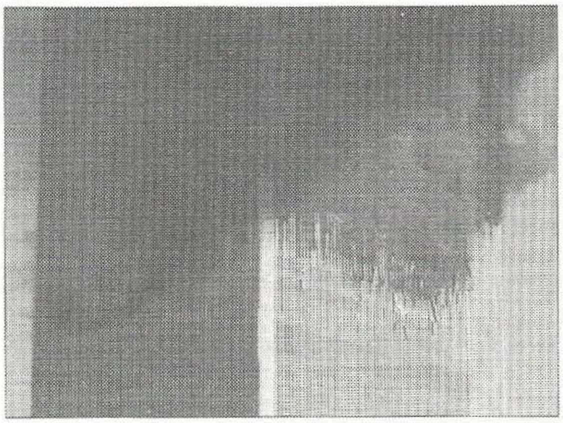
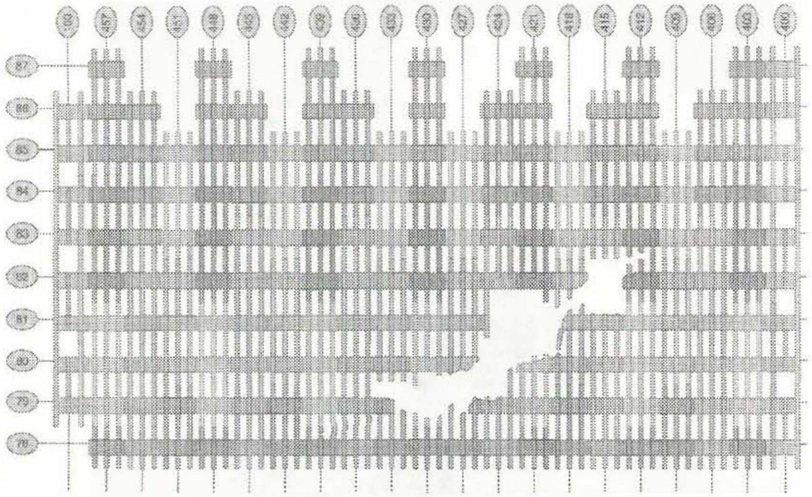


Figure 2-26 Impact damage to the south and east faces of WTC 2.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GENERAL NOTES: (1) Column damage captured from photographs and enhanced videos. (2) Damage to column lines 413-416 at levels 81 and 82 is estimated. (3) There is not sufficient information to detail damage to column lines 408-411 at levels 83-84.

Figure 2-27 Impact damage to exterior columns on the south face of WTC 2.

were fractured by the impact. Photographic evidence suggests that from 27 to 32 columns along the south building face were destroyed over a five-story range. Partial collapse of floors in this zone appears to have occurred over a horizontal length of approximately 70 feet, while floors in other portions of the building appeared to remain intact. It is probable that the columns in the southeast corner of the core also experienced some damage because they would have been in the direct travel path of the fuselage and port engine (Figure 2-25).

It is known that debris from the aircraft traveled completely through the structure. For example, a landing gear from the aircraft that impacted WTC 2 was found to have crashed through the roof of a building located six blocks to the north, and one of the jet engines was found at the corner of Murray and Church Streets. The extent to which debris scattered throughout the impact floors is also evidenced by photographs of the fireballs that occurred as the aircraft struck the building (Figure 2-28). Figure 2-29 shows a portion of the fuselage of the aircraft, lying on the roof of WTC 5.

As described for WTC 1, this debris doubtless caused some level of damage to the structure across the floor plates, including interior framing; core columns at the southeast corner of the core; framing at the north, east, and west walls; and the floor plates themselves. Figure 2-30, showing the eastern side of the north face of the WTC 2 partially hidden behind WTC 1, suggests that damage to the exterior walls was not severe except at the zone of impact. The exact extent of this damage will likely never be known with certainty. It is evident that the structure retained sufficient integrity and strength to remain globally stable for a period of approximately 56 minutes.

There are some important differences between the impact of the aircraft into WTC 2 and the impact into WTC 1. First, United Airlines Flight 175 was flying much faster, with an estimated speed of 590 mph, while American Airlines Flight 11 was flying at approximately 470 mph. The additional speed would have

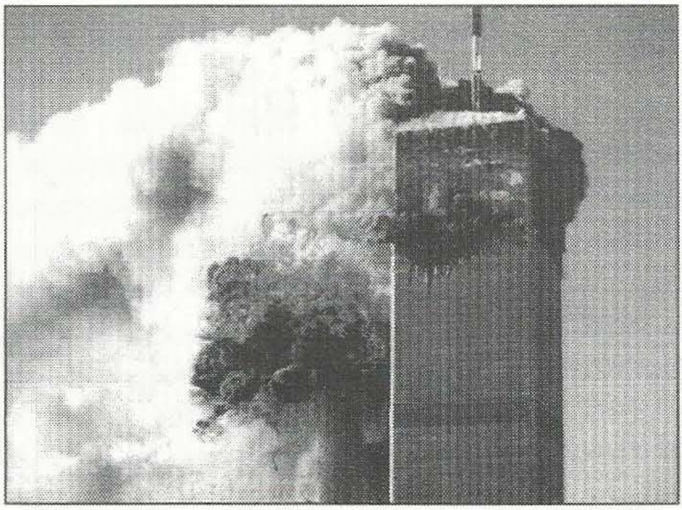

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Figure 2-28 Conflagration and debris exiting the north wall of WTC 2, behind WTC 1.

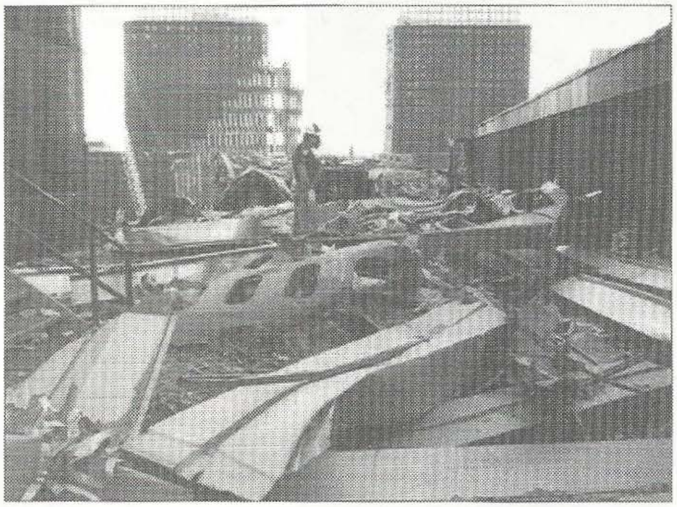

Figure 2-29 A portion of the fuselage of United Airlines Flight 175 on the roof of WTC 5.

given the aircraft a greater ability to destroy portions of the structure. The zone of aircraft impact was skewed toward the southeast corner of WTC 2, while the zone of impact on WTC 1 was approximately centered on the building's north face. The orientation of the core in WTC 2 was such that the aircraft debris would only have to travel 35 feet across the floor before it began to impact and damage elements of the core structure. Finally, the zone of impact in WTC 2 was nearly 20 stories lower than that in WTC 1, so columns in this area were carrying substantially larger loads. It is possible, therefore, that structural damage to WTC 2 was more severe than that to WTC 1, partly explaining why WTC 2 collapsed more quickly than WTC 1.

2.2.2.2 Preliminary Structural Analysis

An approximate linear structural analysis of WTC-2 was performed using SAP-2000 software (CSI 2000) to provide an understanding of the likely stress state in the building following the aircraft impact. The upper 55 stories of the building's exterior-wall frame were explicitly modeled using beam and column elements. This encompassed the entire structure above the zone of impact and about 20 stories below. The lower 55 stories of the exterior were modeled as a "boundary condition" consisting of a perimeter super-beam that was 52 inches deep and about 50 inches wide, supported on a series of springs. A base spring was provided at each column location to represent the axial stiffness of the columns from the 55th floor down to grade. The outrigger trusses at the top of the building were explicitly modeled, using truss-type elements. The interior core columns were modeled as spring elements.

An initial analysis of the building was conducted to simulate the pre-impact condition. In addition to the weight of the floor itself (approximately 54 psf at the building edges and 58 psf at the building sides), a uniform floor loading of 12 psf was assumed for partitions and an additional 20 psf was conservatively assumed to represent furnishings and contents. At the 80th floor level, exterior columns were found to be

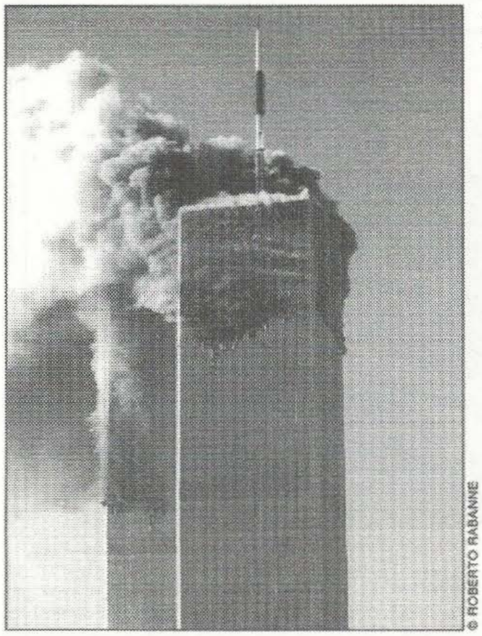

Figure 2-30

North face of WTC 2 opposite the zone of impact on the south face, behind WTC 1.

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approximately uniformly loaded with an average utilization ratio (ratio of actual applied stress to ultimate stress) of under 20 percent. This low utilization ratio is due in part to the unusually close spacing of the columns in this building, which resulted in a very small tributary area for each column. It reflects the fact that wind and deflection considerations were dominant factors in the design. Core columns were more heavily loaded with average calculated utilization ratios of 60 percent, which would be anticipated for these columns, which were designed to resist only gravity loads.

A second analysis was conducted to estimate the demands on columns immediately following aircraft impact and before fire effects occurred. Exterior columns were removed from the model to match the damage pattern illustrated in Figure 2-27. Although some core columns were probably damaged by the aircraft impact, the exact extent of this damage is not known and therefore was not considered in the model. As a result, this analysis is thought to underestimate the true stress state in the columns immediately after impact. The analysis indicates that most of the loads initially carried by the damaged exterior columns were transferred by Vierendeel truss action to the remaining exterior columns immediately adjacent to the impact area. If the floors at this level are assumed to remain intact and capable of providing lateral support to the columns, this raised the utilization ratio for the most heavily loaded column immediately adjacent to the damage area to approximately a value of 1.0. At a value of 1.0, columns would lose stiffness and shift load to adjacent columns. Based on this analysis, it appears that the structure had significant remaining margin against collapse. However, this analysis does not consider damage to the building core, which was likely significant. Columns located further from the damage area are less severely impacted, and columns located only 20 feet away from the damaged area experience almost no increase in demand at all. These data are plotted in Figure 2-31.

The columns immediately above the damage area are predicted to act as tension members, transferring approximately 10 percent of the load initially carried by the damaged columns upward to the outrigger trusses, which, in turn, transfer this load back to the core columns. Not considering any damage to the core columns, utilization ratios on these elements are predicted to increase by about 20 percent at the 80th floor level. In upper stories, where the core columns were more lightly loaded, the increase in utilization ratio is substantially larger and may have approached a value of 1.0. These conditions would have been made more severe by damage to one or more core columns.

2.2.2.3 Fire Development

Following the impact, fires spread throughout WTC 2, similar to the manner previously described for WTC 1. Extensive videotape of the fires' development through the building was recorded from various exterior vantage points. This videotape suggests that, in the minutes immediately preceding the collapse, the most intensive fires occurred along the north face of the building, near the 80th floor level. Just prior to the collapse, a stream of molten material—possibly aluminum from the airliner—was seen streaming out of a window opening at the northeast corner at approximately this level. This is of particular interest because, although the building collapse appears to have initiated at this floor level, the initiation seems to have occurred at the southeast rather than the northeast corner.

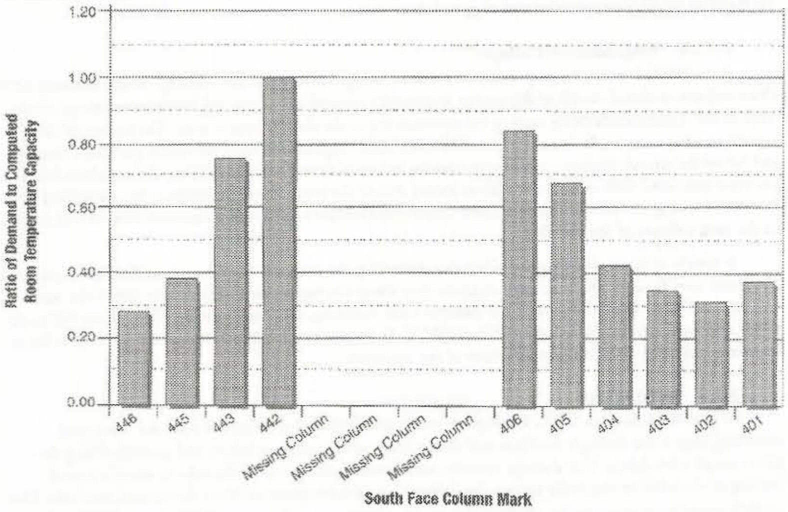

Figure 2-31 Plot of column utilization ratio at the 80th floor of WTC 2, viewed looking outward. (Conservatively assumes columns 407–411 and 440–441 to be missing.)

2.2.2.4 Evacuation

Although less time was available for evacuation of WTC 2 than for WTC 1, and the aircraft hit the building some 16 floors lower than in WTC 1, fewer casualties occurred within this building. The reduced number of casualties to building occupants in WTC 2 may be attributed to the movement of some of the building occupants immediately after the aircraft impact into WTC 1 and before the second aircraft struck WTC 2. Several survivors from WTC 2 stated that, following the impact of the aircraft into WTC 1, a message was broadcast over the loudspeaker system indicating that WTC 2 was secure and that occupants should return to their offices (Scripps 2001, BBC News 2001). Many of these survivors did not heed the announcement and continued to exit the building, using the elevators. Survivors also related reports of individuals who listened to the message, returned to their floors, and did not make it out after the second aircraft impacted WTC 2. Some survivors related that a small number of people traveled to the roof under the assumption that a helicopter rescue was possible (Cauchon 2001b).

2.2.2.5 Initiation of Collapse

The same types of structural behaviors and failure mechanisms previously discussed are equally likely to have occurred in WTC 2, resulting in the initiation of progressive collapse, approximately 56 minutes after the aircraft impact. Review of video footage of the WTC 2 collapse suggests that it probably initiated with a partial collapse of the floor in the southeast corner of the building at approximately the 80th level. This appears to have been followed rapidly by collapse of the entire floor level along the east side, as evidenced by a line of dust blowing out of the side of the building. As this floor collapse occurred, columns along the east face of the building appear to buckle in the region of the collapsed floor, beginning at the south side and progressing to the north, causing the top of the building to rotate toward the east and south and to begin to collapse downward (Figure 2-32). It should be noted that failure of core columns in the southeast corner of the building could have preceded and triggered these events.

2.2.2.6 Progression of Collapse

As in WTC 1, a very large quantity of potential energy was stored in the building, during its construction. Once collapse initiated, much of this energy was rapidly released and converted into kinetic energy, in the form of the rapidly accelerating mass of the structure above the aircraft impact zone. The impact of this rapidly moving mass on the lower structure caused a wide range of structural failures in the floors directly at and below the aircraft impact zone, in turn causing failure of these floors. As additional floor plates failed, the mass associated with each of these floors joined that of the tower above the impact area, increasing the destructive energy on the floors immediately below. This initiated a chain of progressive failures that resulted in the total collapse of the building.

A review of aerial photographs of the site, following the collapse, as well as identification of pieces of structural steel from WTC 2, strongly suggests that while the top portion of the tower fell to the south and east, striking Liberty Street and the Bankers Trust building, the lower portion of the tower fell to the north and west, striking the Marriott Hotel (WTC 3). Again, the debris pattern spread laterally as far as approximately 400–500 feet from the base of the structure.

2.2.3 Substructure

As first WTC 2, then WTC 1 collapsed, nearly 600,000 tons of debris fell onto the Plaza level, punching large holes through the Plaza and the six levels of substructure below, and partially filling the substructure with debris. This damage severely compromised the ability of the slabs to provide lateral bracing of the substructure walls against the induced lateral earth pressures from the unexcavated side. This condition was most severe at the southern side of the substructure, adjacent to WTC 2 and WTC 3. In this region, debris from the collapsed WTC 2 punched through several levels of substructure slab, but did not

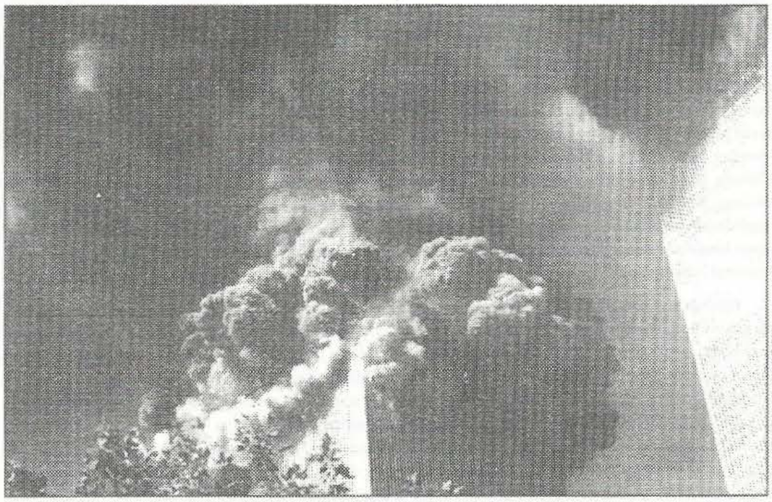

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Figure 2-32 The top portion of WTC 2 falls to the east, then south, as viewed from the northeast.

completely fill the void left behind, leaving the south wall of the substructure in an unbraced condition over a portion of its length.

In early October, large cracks were observed along Liberty Street, indicating that the south wall had started to move into the failed area under the influence of the lateral earth pressures. Mueser-Rutledge Engineers were retained to review the situation and make suitable recommendations. As a temporary measure, sand fill was backfilled against the inside face of the south wall to counterbalance earth pressures on the unexcavated side. Following temporary stabilization of the wall, tiebacks were reinstalled through the wall in a manner similar to that used to stabilize the excavation during the original construction of the development. After these tiebacks were installed, it was possible to begin excavation of the temporary sand backfill and the accumulated debris. Tiebacks were similarly installed at the other exterior substructure walls to provide lateral support as the damaged slabs and debris were excavated and removed from the site.

2.3 Observations and Findings

The structural damage sustained by each of the two buildings as a result of the terrorist attacks was massive. The fact that the structures were able to sustain this level of damage and remain standing for an extended period of time is remarkable and is the reason that most building occupants were able to evacuate safely. Events of this type, resulting in such substantial damage, are generally not considered in building design, and the ability of these structures to successfully withstand such damage is noteworthy.

Preliminary analyses of the damaged structures, together with the fact the structures remained standing for an extended period of time, suggest that, absent other severe loading events such as a windstorm or earthquake, the buildings could have remained standing in their damaged states until subjected to some significant additional load. However, the structures were subjected to a second, simultaneous severe loading event in the form of the fires caused by the aircraft impacts.

The large quantity of jet fuel carried by each aircraft ignited upon impact into each building. A significant portion of this fuel was consumed immediately in the ensuing fireballs. The remaining fuel is believed either to have flowed down through the buildings or to have burned off within a few minutes of the aircraft impact. The heat produced by this burning jet fuel does not by itself appear to have been sufficient to initiate the structural collapses. However, as the burning jet fuel spread across several floors of the buildings, it ignited much of the buildings' contents, causing simultaneous fires across several floors of both buildings. The heat output from these fires is estimated to have been comparable to the power produced by a large commercial power generating station. Over a period of many minutes, this heat induced additional stresses into the damaged structural frames while simultaneously softening and weakening these frames. This additional loading and the resulting damage were sufficient to induce the collapse of both structures.

Because the aircraft impacts into the two buildings are not believed to have been sufficient to cause collapse without the ensuing fires, the obvious question is whether the fires alone, without the damage from the aircraft impact, would have been sufficient to cause such a collapse. The capabilities of the fire protection systems make it extremely unlikely that such fires would develop without some unusual triggering event like the aircraft impact. For all other cases, the fire protection for the tower buildings provided in-depth protection. The first line of defense was the automatic sprinkler protection. The sprinkler system was intended to respond quickly and automatically to extinguish or confine a fire. The second line of defense consisted of the manual (FDNY/Port Authority Fire Brigade) firefighting capabilities, which were supported by the building standpipe system, emergency fire department use elevators, smoke control system, and other features. Manual suppression by FDNY was the principal fire protection mechanism that controlled a large fire that occurred in the buildings in 1975. Finally, the last line of defense was the structural fire resistance. The fire resistance capabilities would not be called upon unless both the automatic and manual suppression systems just described failed. In the incident of September 11, not only did the aircraft impacts disable the first two lines of defense, they also are believed to have dislodged fireproofing and imposed major additional stresses on the structural system.

Had some other event disabled both the automatic and manual suppression capabilities and a fire of major proportions occurred while the structural framing system and its fireproofing remained intact, the third line of defense, structural fireproofing, would have become critical. The thickness and quality of the fireproofing materials would have been key factors in the rate and extent of temperature rise in the floor trusses and other structural members. In the preparation of this report, there has not been sufficient analysis to predict the temperature and resulting change in strength of the individual structural members in order to approximate the overall response of the structure. Given the redundancy in the framing system and the capability of that system to redistribute load from a weakened member to other parts of the structural system, it is impossible, without extensive modeling and other analysis, to make a credible prediction of how the buildings would have responded to an extremely severe fire in a situation where there was no prior structural damage. Such simulations were not performed within the scope of this study, but should be performed in the future.

Buildings are designed to withstand loading events that are deemed credible hazards and to protect the public safety in the event such credible hazards are experienced. Buildings are not designed to withstand any event that could ever conceivably occur, and any building can collapse if subjected to a sufficiently extreme loading event. Communities adopt building codes to help building designers and regulators determine those loading events that should be considered as credible hazards in the design process. These building codes are developed by the design and regulatory communities themselves, through a voluntary committee consensus process. Prior to September 11, 2001, it was the consensus of these communities that aircraft impact was not a sufficiently credible hazard to warrant routine consideration in the design of buildings and, therefore, the building codes did not require that such events be considered in building design. Nevertheless, the design of WTC 1 and WTC 2 did include at least some consideration of the probable response of the buildings to an aircraft impact, albeit a somewhat smaller and slower moving aircraft than those actually involved in the September 11 events. Building codes do consider fire as a credible hazard and include extensive requirements to control the spread of fire throughout buildings, to delay the onset of fire-induced structural collapse, and to facilitate the safe egress of building occupants in a fire event. For fire-protected steel-frame buildings, like WTC 1 and WTC 2, these code requirements had been deemed effective and, in fact, prior to September 11, there was no record of the fire-induced-collapse of such structures, despite some very large uncontrolled fires.

The ability of the two towers to withstand aircraft impacts without immediate collapse was a direct function of their design and construction characteristics, as was the vulnerability of the two towers to collapse a result of the combined effects of the impacts and ensuing fires. Many buildings with other design and construction characteristics would have been more vulnerable to collapse in these events than the two towers, and few may have been less vulnerable. It was not the purpose of this study to assess the code-conformance of the building design and construction, or to judge the adequacy of these features. However, during the course of this study, the structural and fire protection features of the buildings were examined. The study did not reveal any specific structural features that would be regarded as substandard, and, in fact, many structural and fire protection features of the design and construction were found to be superior to the minimum code requirements.

Several building design features have been identified as key to the buildings' ability to remain standing as long as they did and to allow the evacuation of most building occupants. These included the following:

- robustness and redundancy of the steel framing system
- adequate egress stairways that were well marked and lighted
- conscientious implementation of emergency exiting training programs for building tenants

Similarly, several design features have been identified that may have played a role in allowing the buildings to collapse in the manner that they did and in the inability of victims at and above the impact floors to safely exit. These features should not be regarded either as design deficiencies or as features that should be prohibited in future building codes. Rather, these are features that should be subjected to more detailed evaluation, in order to understand their contribution to the performance of these buildings and how they may perform in other buildings. These include the following:

- the type of steel floor truss system present in these buildings and their structural robustness and redundancy when compared to other structural systems
- use of impact-resistant enclosures around egress paths
- resistance of passive fire protection to blasts and impacts in buildings designed to provide resistance to such hazards
- grouping emergency egress stairways in the central building core, as opposed to dispersing them throughout the structure

During the course of this study, the question of whether building codes should be changed in some way to make future buildings more resistant to such attacks was frequently explored. Depending on the size of the aircraft, it may not be technically feasible to develop design provisions that would enable all structures to be designed and constructed to resist the effects of impacts by rapidly moving aircraft, and the ensuing fires, without collapse. In addition, the cost of constructing such structures might be so large as to make this type of design intent practically infeasible.

Although the attacks on the World Trade Center are a reason to question design philosophies, the BPS Team believes there are insufficient data to determine whether there is a reasonable threat of attacks on specific buildings to recommend inclusion of such requirements in building codes. Some believe the likelihood of such attacks on any specific building is deemed sufficiently low to not be considered at all. However, individual building developers may wish to consider design provisions for improving redundancy and robustness for such unforeseen events, particularly for structures that, by nature of their design or occupancy, may be especially susceptible to such incidents. Although some conceptual changes to the building codes that could make buildings more resistant to fire or impact damage or more conducive to occupant egress were identified in the course of this study, the BPS Team felt that extensive technical, policy, and economic study of these concepts should be performed before any specific code change recommendations are developed. This report specifically recommends such additional studies. Future building code revisions may be considered after the technical details of the collapses and other building responses to damage are better understood.

2.4 Recommendations

The scope of this study was not intended to include in-depth analysis of many issues that should be explored before final conclusions are reached. Additional studies of the performance of WTC 1 and WTC 2 during the events of September 11, 2001, and of related building performance issues should be conducted. These include the following:

- During the course of this study, it was not possible to determine the condition of the interior structure of the two towers, after aircraft impact and before collapse. Detailed modeling of the aircraft impacts into the buildings should be conducted in order to provide understanding of the probable damage state immediately following the impacts.
- Preliminary studies of the growth and heat flux produced by the fires were conducted. Although these studies provided useful insight into the buildings' behavior, they were not of sufficient detail to permit an understanding of the probable distribution of temperatures in the buildings at various stages of the event and the resulting stress state of the structures as the fires progressed. Detailed modeling of the fires should be conducted and combined with structural modeling to develop specific failure modes likely to have occurred.
- The floor framing system for the two towers was complex and substantially more redundant than typical bar joist floor systems. Detailed modeling of these floor systems and their connections should be conducted to understand the effects of localized overloads and failures to determine ultimate failure modes. Other types of common building framing should also be examined for these effects.
- The fire-performance of steel trusses with spray-applied fire protection, and with end restraint conditions similar to those present in the two towers, is not well understood, but is likely critical to the building collapse. Studies of the fire-performance of this structural system should be conducted.
- Observation of the debris generated by the collapse of the towers and of damaged adjacent structures suggests that spray-applied fireproofing may be vulnerable to mechanical damage from blasts and impacts. This vulnerability is not well understood. Tests of these materials should be conducted to understand how well they withstand such mechanical damage and to determine whether it is appropriate and feasible to improve their resistance to such damage.

- In the past, tall buildings have occasionally been damaged, typically by earthquakes, and experienced collapse within the damaged zones. Those structures were able to arrest collapse before they progressed to a state of total collapse. The two WTC towers were able to arrest collapse from the impact damage, but not from the resulting fires when combined with the impact effects of the aircraft attacks. Studies should be conducted to determine, given the great size and weight of the two towers, whether there are feasible design and construction features that would permit such buildings to arrest or limit a collapse, once it began.

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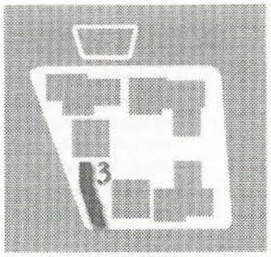


William Baker

3 WTC 3

3.1 Design and Construction Features

WTC 3 (also known as the World Trade Center Hotel, the Vista Hotel, and the Marriott Hotel) was almost completely destroyed as a result of the September 11 attacks due to debris from the collapse of the adjacent WTC 1 and WTC 2. This chapter describes the structural design and construction features of the building as well as details of its collapse. The information contained in this section is based on architectural and structural design drawings dating to 1978, photographs, written reports and articles, videotape recordings, and interviews with Marriott staff. Steel shop drawings were not available for review.

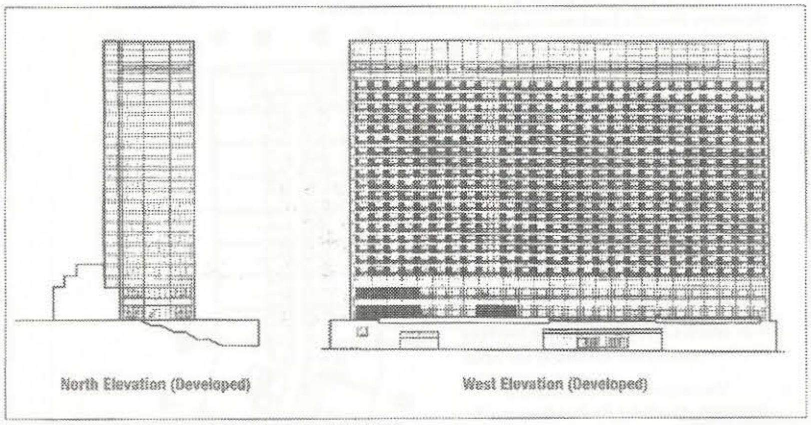
3.1.1 Project Overview

WTC 3 was a steel-framed hotel building located on the southwest corner of the WTC Complex immediately to the south of WTC 1 (the north tower) and to the west of WTC 2 (the south tower). The site was bounded on the west by West Street and on the south by Liberty Street. The building was designed in 1978/1979 by Skidmore, Owings & Merrill (SOM), architects; Weiskopf & Pickworth, structural engineers; and Jaros, Baum & Bolles, mechanical engineers. Weiskopf & Pickworth designed the superstructure for the hotel. Skilling, Helle, Christiansen, and Robertson designed the transfer system between the hotel column grid and the below grade parking grid as well as the structure below the transfer system. WTC 3 opened in 1981 and housed the 825-room Vista hotel. The original owner and operator of the hotel was Hilton International, but the property was sold in 1996 to Marriott Hotels (Harris 2001). Marriott operated the hotel from 1996 until the attacks on September 11, 2001.

3.1.2 Building Description

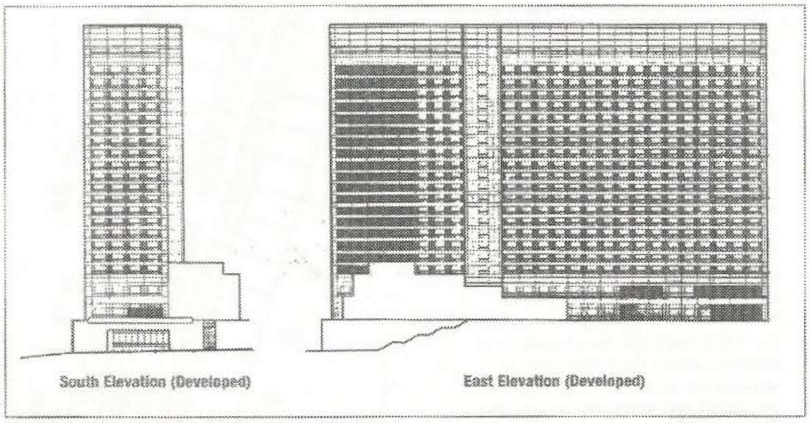
The building had 22 stories above grade and 6 stories below grade (labeled B1 through B6.) The roof parapet line was approximately 242 feet above West Street. The north and west elevations are shown in Figure 3-1 and the south and east elevations are shown in Figure 3-2, as taken from the original architectural drawings from SOM. The first level below grade provided loading docks, building services, and other functions for the hotel. The other levels below grade were part of the overall WTC complex and provided parking space. The ground level housed the hotel lobby and ballroom. The two stories above the ground level lobby were occupied by restaurants and conference facilities. The next 18 stories accommodated the approximately 825 guest suites. A health club and mechanical services were located on the top floor of the building.

The building was a long rectangle in plan with an obtuse angle change at approximately one-third of the length of the building from the north. The typical floor of the building was approximately 64 feet wide and 330 feet long, with floor story heights of 9 feet 6 inches. Elevators were located at the east side of the building, roughly centered north to south, directly opposite the building entry, which was located on the west side of the building. The general arrangement of the hotel suites is indicated in Figure 3-3.


North Elevation (Developed)

West Elevation (Developed)

Figure 3-1 Developed north and west elevations (SOM 1979).


South Elevation (Developed)

East Elevation (Developed)

Figure 3-2 Developed south and east elevations (SOM 1979).

3.1.3 Structural Description

The primary structural frame of WTC 3 was composed of rolled, wide-flange structural steel columns, floor beams, and girders. The column grid for the building consisted of approximately twelve 26-foot-wide bays in the north-south direction with non-typical bays at the south end of the building and at the location of the plan angle change. In the east-west direction, there were three bays with column spacings of 18 feet 9-7/8 inches, 22 feet 6 inches, and 18 feet 9-3/4 inches. Steel columns were standard wide-flange W14-series shapes throughout (up to W14x500 at the 2nd floor). Details of column splices were not indicated on the structural design drawings.

The hotel structural system was transferred from the hotel column grid to the substructure grid at different levels. Most of the column transfers occurred right above the lobby level to accommodate the large open space required for the hotel lobby and ballroom. Some column transfers also occurred below the lowest guestroom floor. Skilling, Helle, Christiansen, and Robertson originally designed all the transfers. Following the 1993 bombing, extensive renovations to the hotel required additional transfer girders above the lobby level. These new transfers were designed by Leslie E. Robertson Associates (*Engineering News Record* 1994). Details of the 2nd floor transfer system are not included in this report.

Structural steel was ASTM A36 throughout except for the 2nd floor transfer girders, which were ASTM A572-Grade 50. Typical floor beams were W16 and W21 rolled shapes, spaced 13 feet 0 inches on center. The connection design reactions for the floor beams were specified to be based on the uniformly loaded beam end shear. Typical simple shear connection types are not indicated on the design drawings. Although the structural drawings prepared by Weiskopf & Pickworth indicate typical details of stud shear connectors, the total extent of composite design is unclear. The drawings show that composite action was used all through the 4th floor and on a few elements of the 21st floor. There is no indication that the typical guestroom floors (i.e., 5th through 20th floors) made use of composite action. The design drawings specified that all steel was to be fireproofed, and that all steel pieces weighing less than 28 pounds per linear foot were to have double spray-on thickness for fireproofing. The typical hotel floor framing plan is shown in Figure 3-4, as taken from the original structural design drawings prepared by Weiskopf & Pickworth.

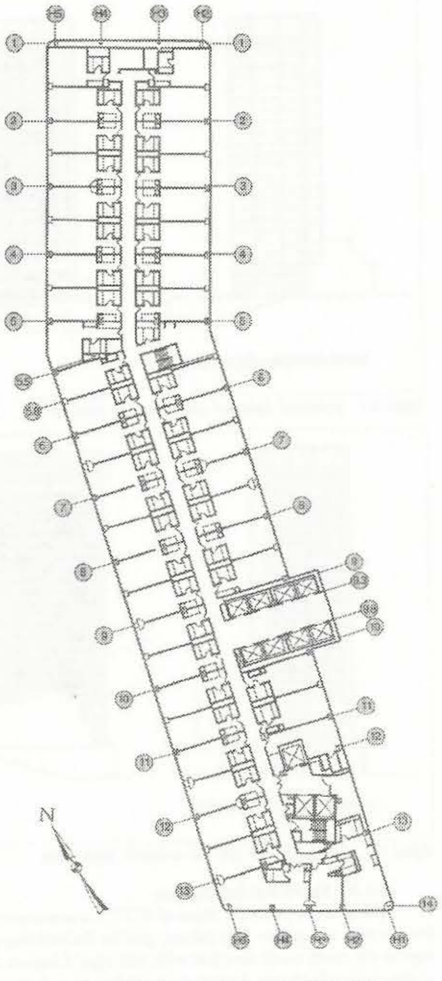


Figure 3-3 Typical hotel floor plan (SOM 1981).

Uniform floor live load allowance was specified to be 40 pounds per square foot (psf) for the typical guest room areas. Uniform floor dead load allowance included the weight of the floor structure, 10 psf for partitions, and 4 psf for ceilings and finishes. The roof design live load was 30 psf throughout.

The typical guestroom floor slabs spanned 13 feet 0 inches between floor beams and consisted of 3-inch-deep composite steel floor deck (noted as 20 gauge on the original Weiskopf & Pickworth design drawings), with 3-1/4-inch lightweight concrete topping above the top of the steel deck and welded wire fabric reinforcement. The top of the slab was at the same elevation for the guestrooms, restrooms, and corridors. However, in the restrooms and corridors, the floor beams were raised 1 inch to provide increased headroom for service ducts. To accommodate this situation, the steel deck was only 2 inches deep in these areas. The edge of slab was 1 foot 9 inches beyond the column line and was supported by a secondary W14 spandrel beam placed outboard of the perimeter column line.

Resistance to lateral loads in the long (north-south) direction was provided through parallel moment resisting beam/column frames located along all four major column lines. Generally, W16-series girders were utilized for the two interior moment frame lines and W21-series girders for the two exterior moment frame lines. In the short transverse (east-west) direction, resistance to lateral loads was provided through a combination of concentrically and eccentrically diagonally braced frames. These braced frames were located along partition lines between rooms and around the central north-south-running corridor. Each major column line, with the exception of the north and south facades, was diagonally braced (26 feet 0 inches on center). In combination, each column in the

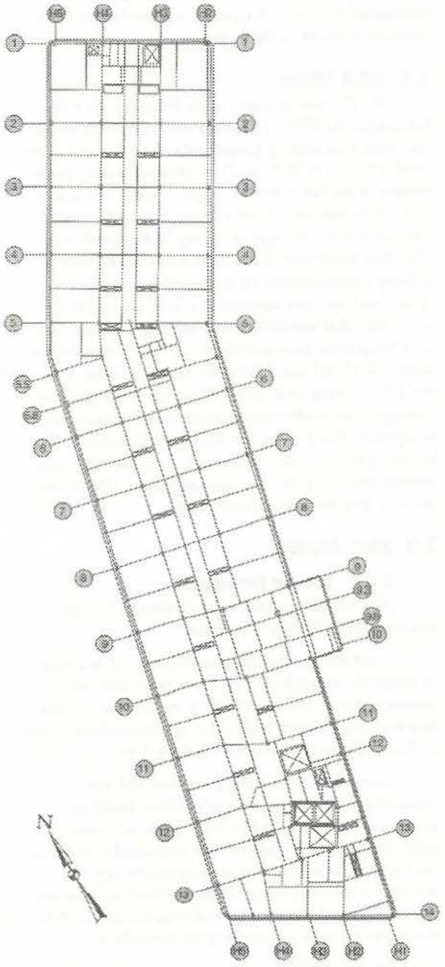


Figure 3-4 Typical hotel floor framing plan (Weiskopf & Pickworth 1979a).

building participated in the lateral load resisting system, with most columns involved in resistance along both orthogonal directions. A typical transverse braced frame elevation is shown in Figure 3-5.

3.2 1993 Attack

WTC 3 was damaged in the February 26, 1993, bombing of the WTC. The bomb was set off in the second basement level parking garage under the north end of the hotel, adjacent to WTC 1. The explosion caused a major collapse of the slab at level B2 (approximately 130 feet by 130 feet in dimension) and a major, but smaller, slab collapse at Level B1 (approximately 50 feet by 80 feet). The West Street level (Concourse level) had a limited collapse (approximately 18 feet by 22 feet). Level 1 (Plaza level) was not ruptured, but had an area (10 feet by 10 feet) that was deflected upward. (The above data were taken from Isner and Klem [1994]). There were no slabs at levels B3 and B4 directly below the blast, and the debris landed on level B5. There was also significant damage to non-loadbearing partition walls and mechanical equipment. The damage was subsequently repaired. The bombing has been more extensively described in several reports, including those by Isner and Klem (1994) and the U.S. Fire Administration (1993).

3.3 2001 Attacks

3.3.1 Fire and Evacuation

The following account was developed through interviews with Marriott Hotel staff.

Small fires on the top floor were ignited as a result of projectiles through the roof, most likely after the impact of the aircraft with WTC 1. At least one of these fires was located in the health club on the top floor. Some jet fuel was reportedly involved in these fires.

Evacuation of the hotel guests and staff was initiated shortly after ignition of the fires. Building occupants were initially directed to the hotel lobby. Later, the building occupants were instructed to evacuate the building. It is unknown whether the fire alarm system was activated in the building. Hotel staff and fire service personnel alerted other building occupants while moving in the corridors on the guest room floors.

All of the building occupants were evacuated from the building. However, two members of the hotel

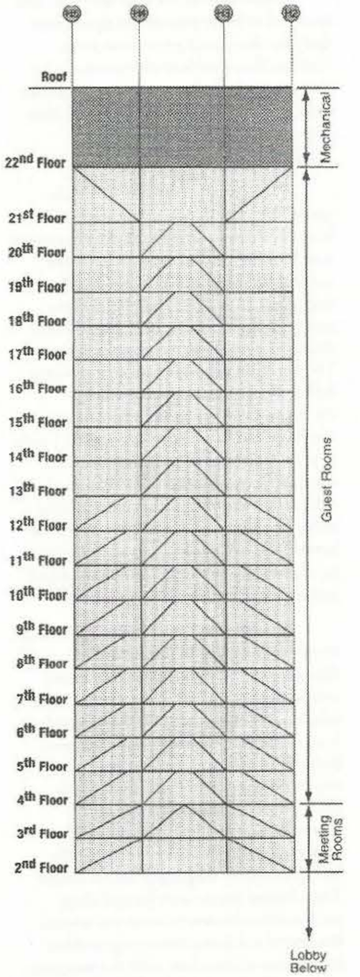

H5
H4
H3
H2
Roof
22nd Floor
21st Floor
20th Floor
19th Floor
18th Floor
17th Floor
16th Floor
15th Floor
14th Floor
13th Floor
12th Floor
11th Floor
10th Floor
9th Floor
8th Floor
7th Floor
6th Floor
5th Floor
4th Floor
3rd Floor
2nd Floor
Mechanical
Guest Rooms
Meeting Rooms
Lobby Below

Figure 3-5 Typical transverse bracing elevation (Weiskopf & Pickworth 1979b).

management team had each re-entered the building to check on the safety of guests and firefighters, and incurred fatal injuries on the guest room floors upon collapse of WTC 2.

3.3.2 Building Response

The response of WTC 3 to the September 11 events is complex and noteworthy. WTC 3 was subjected to two loading events. The first event involved the collapse of WTC 2, which stood immediately east of WTC 3. Due to its proximity to WTC 2, substantial amounts of debris fell directly on the roof of WTC 3. Figure 3-6 shows large portions of the prefabricated assemblies from WTC 2 falling on top of WTC 3.

Debris from WTC 2 struck the building with sufficient force to crush approximately 16 stories in the center of the building, as shown in Figure 3-7. In spite of this extensive damage, the collapse did not continue down to the foundations or extend horizontally to the edges of the structure. In fact, the two

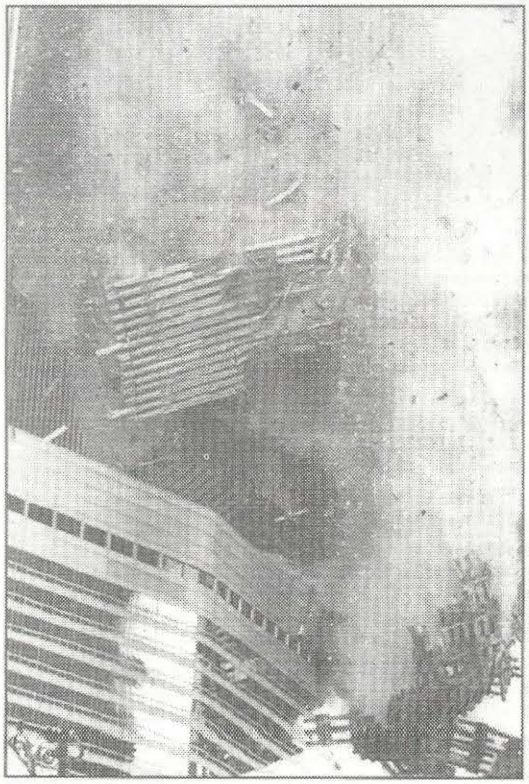


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Figure 3-6
Exterior columns from WTC 2 collapse falling on the southern part of WTC 3.

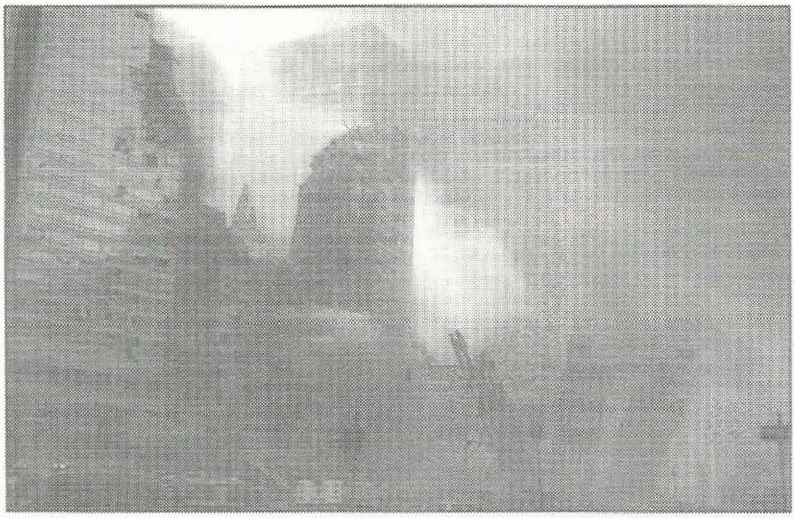

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Figure 3-7 Partial collapse of WTC 3 after collapse of WTC 2.

northernmost bays (approximately 60 feet) remained intact all the way to the roof. A similar, but lesser condition existed in the southern bays. Even in the center of the building, the collapse stopped at approximately the 7th floor. This arrested collapse implies that the structure was sufficiently strong and robust to absorb the energy of the falling debris and collapsed floors, but at the same time the connections between the destroyed and remaining framing were able to break apart without pulling down the rest of the structure. This complex behavior resulted in the survival of large portions of the building following the collapse of WTC 2.

The second loading event was the collapse of WTC 1. Debris from WTC 1 fell along the entire length of the hotel. Lower floors at the southwest end of WTC 3 survived although they suffered extensive damage. [illegible]

An FDNY fire company was in the building during the collapses of both WTC 1 and WTC 2 and survived. The firefighters were near the top of the building in the process of making sure that there were no civilians present in the building, when the south tower collapsed. Firefighter Heinz Kothe is quoted as saying, "We had no idea what had happened. It just rocked the building. It blew the door to the stairwell open, and it blew the guys up near the door halfway down a flight of stairs. I got knocked down to the landing. The building shook like buildings just don't shake." Subsequently, the firefighters were in the lower portion of the southwest corner of the building when the north tower collapsed (Court 2001).

The Chief Engineer of the Port Authority of New York and New Jersey (hereafter referred to as the Port Authority), Frank Lombardi, was in the lobby of WTC 3 with other Port Authority executives during the collapse of WTC 2. They survived the collapse and were eventually able to leave the building (Robin and Tachman 2001).

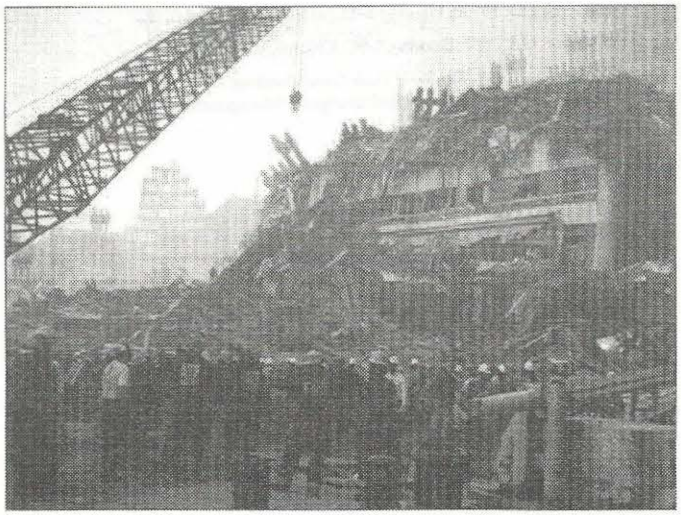

Figure 3-8 Remains of WTC 3 after collapse of WTC 1 and WTC 2.

3.4 Observations

WTC 3 was subjected to extraordinary loading from the impact and weight of debris from the two adjacent 110-story towers. It is noteworthy that the building resisted both horizontal and vertical progressive collapse when subjected to debris from WTC 2. The overloaded portions were able to break away from the rest of the structure without pulling it down, and the remaining structural system was able to remain stable and support the debris load. The structure was even capable of protecting occupants on lower floors after the collapse of WTC 1.

3.5 Recommendations

WTC 3 should be studied further to understand how it resisted progressive collapse.

3.6 References

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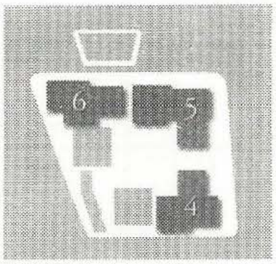
Jonathan Barnett
Richard Gewain
Ramon Gilsanz
Harold "Bud" Nelson



4 *WTC 4, 5, and 6*

4.1 Design and Construction Features

WTC 4, 5, and 6 are eight- and nine-story steel-framed office buildings, located on the north and east sides of the WTC Plaza, that were built circa 1970. The buildings had a range of occupancies, including standard office and retail space. There were underground parking facilities and access to the WTC Concourse, as well as the Port Authority Trans-Hudson (PATH) and New York City subway system.

Because of their close proximity to WTC 1 and WTC 2, all three buildings were subjected to severe debris impact damage when the towers collapsed, as well as the fires that developed from the debris. Most of WTC 4 collapsed when impacted by the exterior column debris from WTC 2; the remaining section had a complete burnout. WTC 5 and WTC 6 were impacted by exterior column debris from WTC 1 that caused large sections of localized collapse and subsequent fires spread throughout most of the buildings. All three buildings also were able to resist progressive collapse, in spite of the extensive local collapses that occurred.

This chapter describes the design and construction features of these buildings and observed damages. Site observations of damage in WTC 5 and WTC 6 were conducted by team members, although access in WTC 6 was severely limited. WTC 4 was declared unsafe, and no access was allowed.

All three buildings were designed by Leslie E. Robertson Associates and had similar design features, although their configurations were somewhat different. Therefore, because most site observations were made in WTC 5, the following discussion focuses primarily on this building, and is assumed to be applicable to all three structures.

4.1.1 Structural Design Features

WTC 5 was located in the northeast corner of the WTC Plaza. The nine-story building was L-shaped in plan, with overall dimensions of 330 feet by 420 feet, providing approximately 120,000 square feet per floor (Figure 4-1). Floors were constructed of 4-inch-thick lightweight concrete fill on metal deck (with a combined thickness of 5-1/2 inches), supported by structural steel framing. The steel floor frame had shear studs welded to the top flange to create a composite floor system with the concrete deck. Wide-flange structural columns were placed on a regular 30-foot-square grid pattern. The floor plates cantilevered out 15 feet from the exterior column lines on all sides. To support this cantilever and provide the basic lateral resistance for the structure, a pair of W27 wide-flange beams were provided at each column line. These doubled wide-flange beams extended between the two outermost column lines, forming a moment-resisting frame, and cantilevered past the outer columns.

Floor beams were typically W16 wide-flange members. At interior column lines, a column-tree system was used, in which a 4-foot-long stub was shop-welded to the column on each side, and the floor girder was

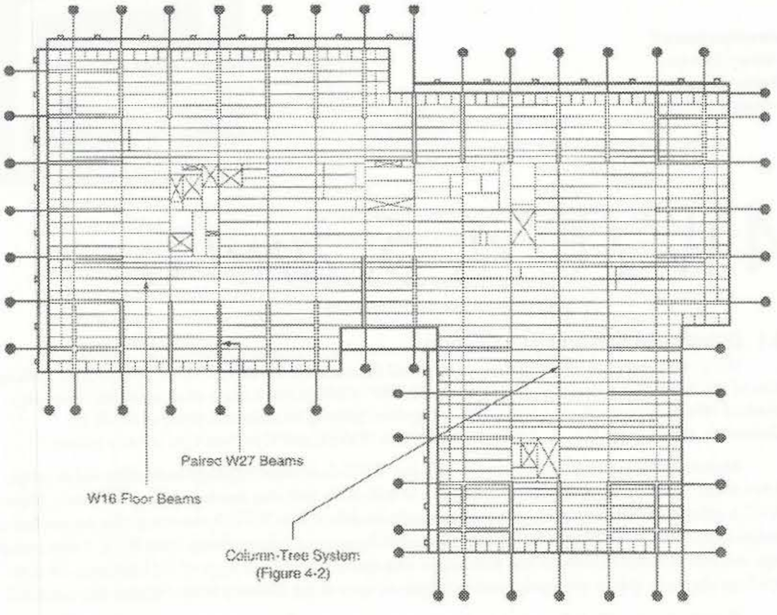


Figure 4-1 Typical floor plan for WTC 5 (Worthington, Skilling, Helle & Jackson 1968).

simply connected, with shear tabs, to the cantilevers (Figure 4-2). Floor 9 and roof level framing was conventional for steel-frame construction and did not include a column-tree system, as illustrated in Figure 4-3.

4.1.2 Fire Protection Features

WTC 5 appeared to have typical combustible contents for an office building, including furnishings, paper, etc. No evidence of any other type of fire load was noted. There appeared to be local concentrations of heavier fire loads, such as file storage, in some areas of the floors that exceeded the average combustible fire load normally associated with office occupancies. A raised sub-floor was present in a portion of the 6th floor, indicative of a computer room or electronic equipment area.

At the time of the September 11 attacks, WTC 5 was equipped with an automatic sprinkler system. The columns had the characteristics of a 3-hour fire resistance rating. The floor assembly (floor and floor beams) had the characteristics of a 2-hour fire resistance rating. Typical fire resistance ratings of roofs of this type are 1-1/2 hours. The exterior non-loadbearing walls did not appear to have a fire resistance rating.

Based on the building plans and on-site observations of WTC 5, the fire protection material for the steel members was a spray-applied mineral fiber applied directly to the steel columns, beams, and girders. Sprayed fiber is a commonly used low-density material.

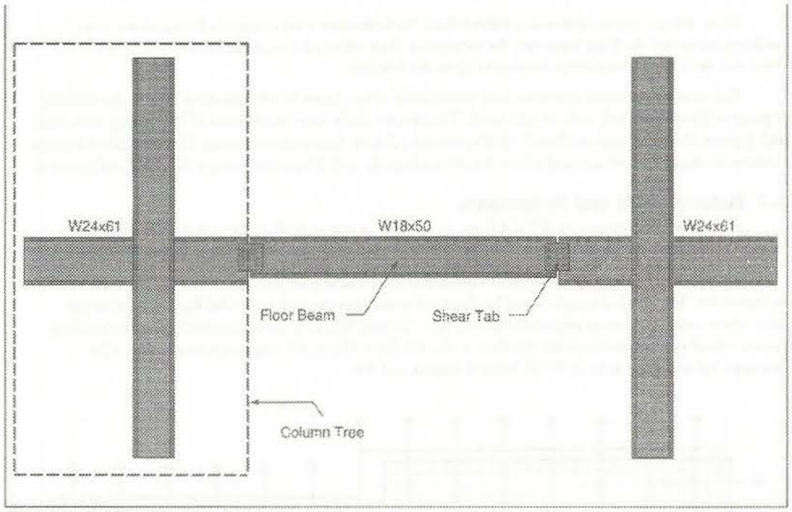

W24x61
W18x50
W24x61
Floor Beam
Shear Tab
Column Tree

Figure 4-2 Typical column-tree system (not to scale).

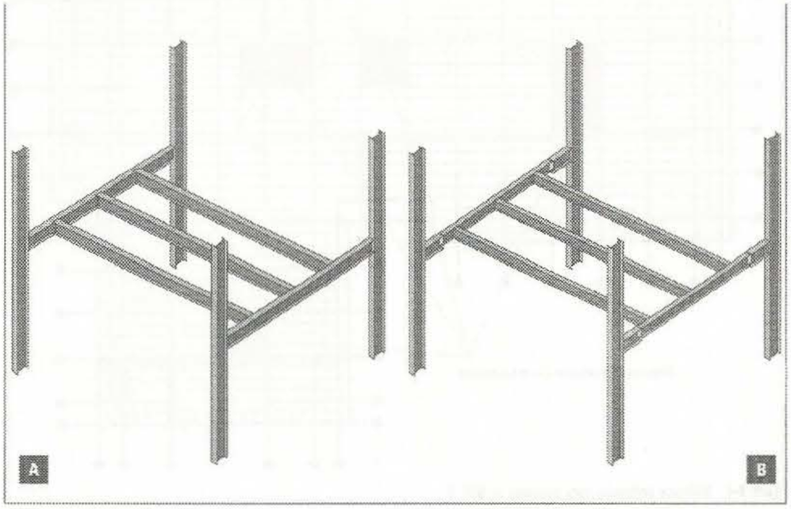


Figure 4-3 Typical interior bay framing in WTC 5. (A) Floor 9 and roof level. (B) Floors 4, 5, 6, 7, and 8.

There was one continuous open escalator from the Concourse level to the 4th floor and one open escalator connected the Plaza level with the mezzanine. Four stairways connected the Plaza level to the 8th floor, and three of those stairways continued up to the 9th floor.

The stairway enclosure core areas were constructed of two layers of 5/8-inch-thick Type-X (fire resistant) gypsum wallboard on both sides of steel studs. The elevator shafts were constructed of HT shaped steel studs and gypsum wallboard and coreboard, which provides a 2-hour fire resistance rating. This type of wall framing permits construction of elevator shafts from the office side of the wall. These core areas are illustrated in Figure 4-4.

4.2 Building Loads and Performance

There was major impact to WTC 4 from the collapse of one or both of the twin towers (most likely WTC 2) that destroyed all but the northern 50 feet of the building. Extensive damage is evident in Figure 4-5.

WTC 5 was damaged by impact and subsequent fires. The impact damage areas in WTC 5 are shown in Figure 4-6. The debris damage caused localized collapses from the roof to the 3rd floor in most of the areas where exterior columns impacted the structure. Ensuing fires that burned unchecked in the building caused a localized collapse from the 9th floor to the 4th floor. Figure 4-7 diagrammatically shows the damaged and collapsed areas of WTC 5 due to impact and fire.

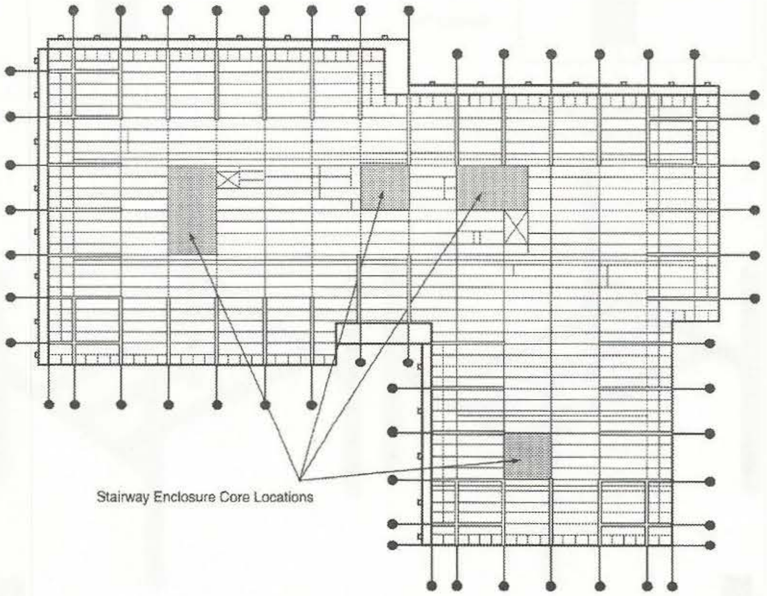


Figure 4-4 Stairway enclosure core locations in WTC 5.

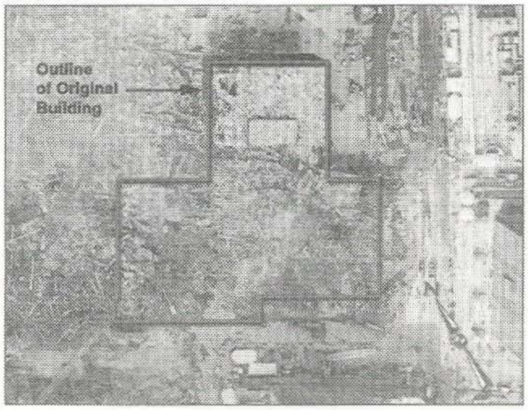

Outline
of Original
Building

Figure 4-5
Damage to WTC 4.

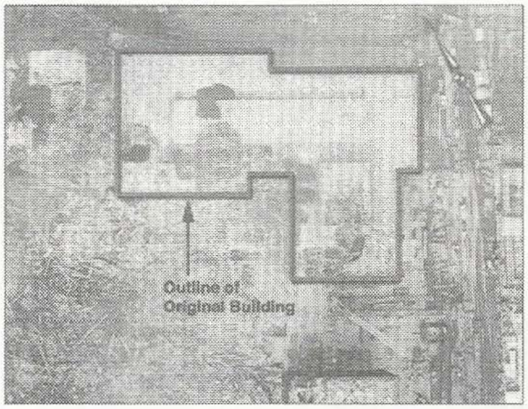

Outline of
Original Building

Figure 4-6
Damage to WTC 5.

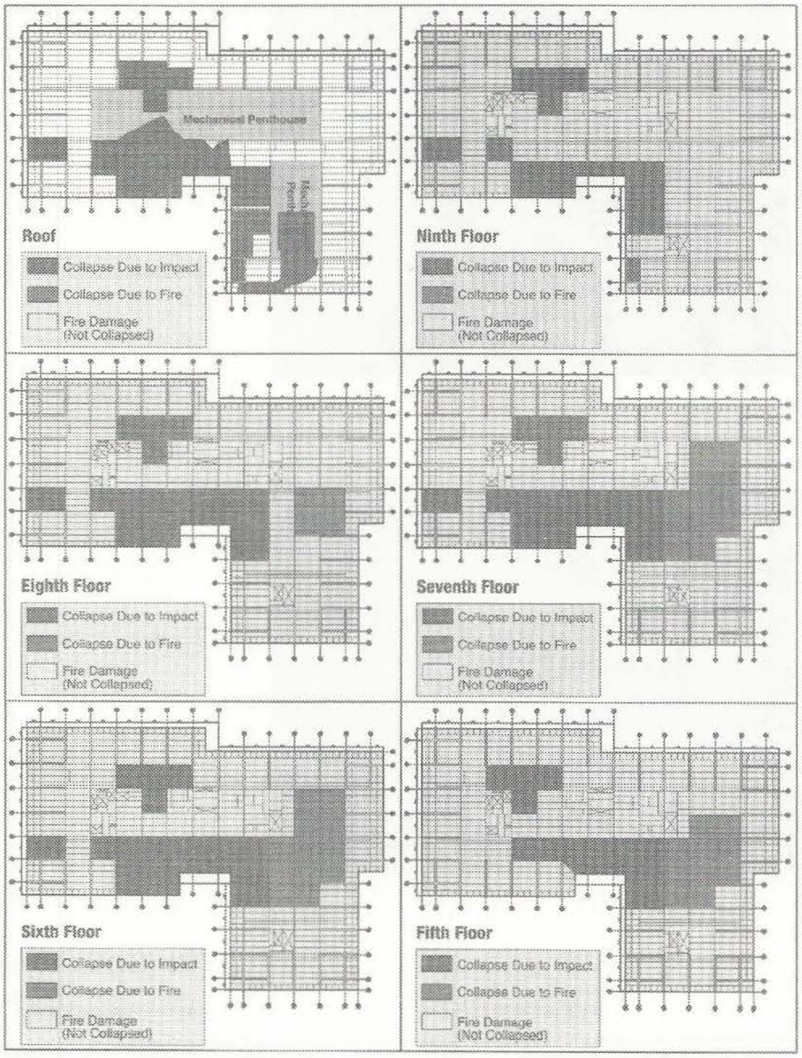

Mechanical Penthouse
Mech. Penth.
Roof
Collapse Due to Impact
Collapse Due to Fire
Fire Damage (Not Collapsed)
Ninth Floor
Collapse Due to Impact
Collapse Due to Fire
Fire Damage (Not Collapsed)
Eighth Floor
Collapse Due to Impact
Collapse Due to Fire
Fire Damage (Not Collapsed)
Seventh Floor
Collapse Due to Impact
Collapse Due to Fire
Fire Damage (Not Collapsed)
Sixth Floor
Collapse Due to Impact
Collapse Due to Fire
Fire Damage (Not Collapsed)
Fifth Floor
Collapse Due to Impact
Collapse Due to Fire
Fire Damage (Not Collapsed)

Figure 4-7 Approximate locations of damaged floor areas in WTC 5.

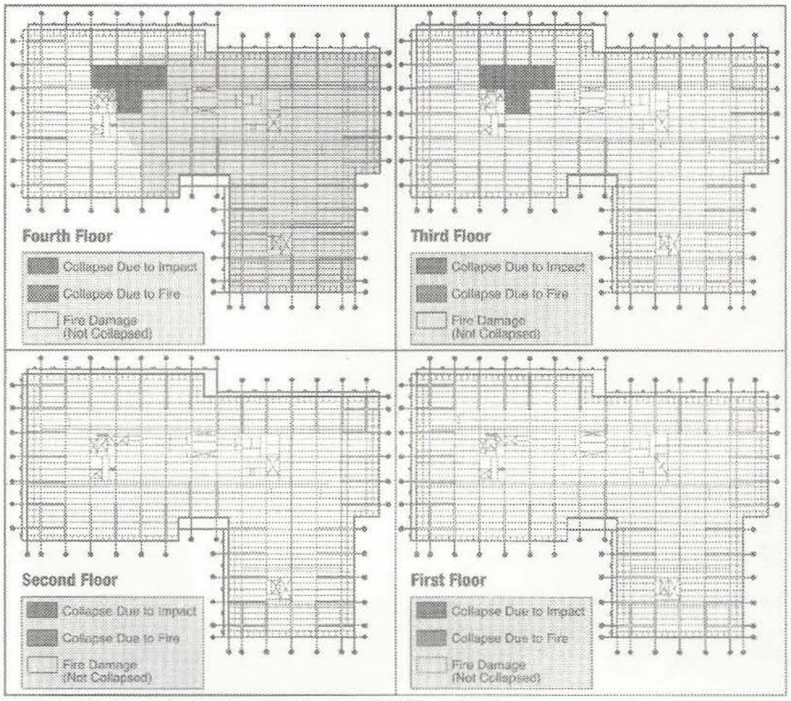

Fourth Floor
Collapse Due to Impact
Collapse Due to Fire
Fire Damage (Not Collapsed)
Third Floor
Collapse Due to Impact
Collapse Due to Fire
Fire Damage (Not Collapsed)
Second Floor
Collapse Due to Impact
Collapse Due to Fire
Fire Damage (Not Collapsed)
First Floor
Collapse Due to Impact
Collapse Due to Fire
Fire Damage (Not Collapsed)

Figure 4-7 Approximate locations of damaged floor areas in WTC 5 (continued).

WTC 6 suffered significant impact and fire damage from the collapse of WTC 1, as shown in Figure 4-8. Most of the impact appears to have been in the center of the building, where the damage extended to the ground level. Figures 4-9 and 4-10 illustrate the magnitude of the damage.

4.2.1 Impact Damage to WTC 5

The impact was most severe at the inside corner at the junction of the north-south and east-west portions of the L-shaped building, as well as at a limited region in the west region of the north-south portion.

The debris impact caused partial collapses of the roofs and some floors beneath the points of impact in all three buildings. In WTC 5, it caused partial collapses down to floor 3. The debris impact also ignited fires that spread throughout the building.

Many areas of buckled steel-beam flanges appeared to have been caused by debris impact. There were 3-1/2 inch steel pipe façade supports along the building perimeter, many of which had buckled from taking part of the collapsed floor loads above the pipe supports (see Figure 4-11). In areas that locally collapsed from impact, some of the floor beams separated from the floor deck and others separated at the welded connection.

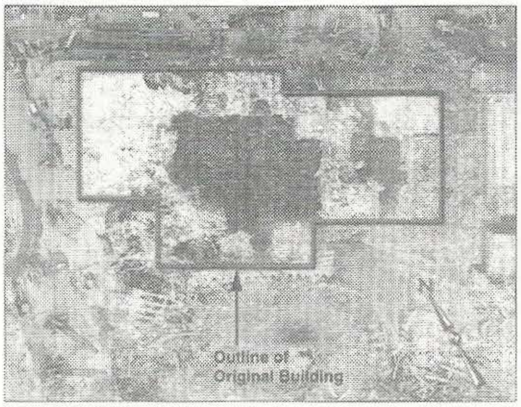

Outline of
Original Building
N

Figure 4-8
Damage to WTC 6. Note the edge of WTC 5 on the right hand side.

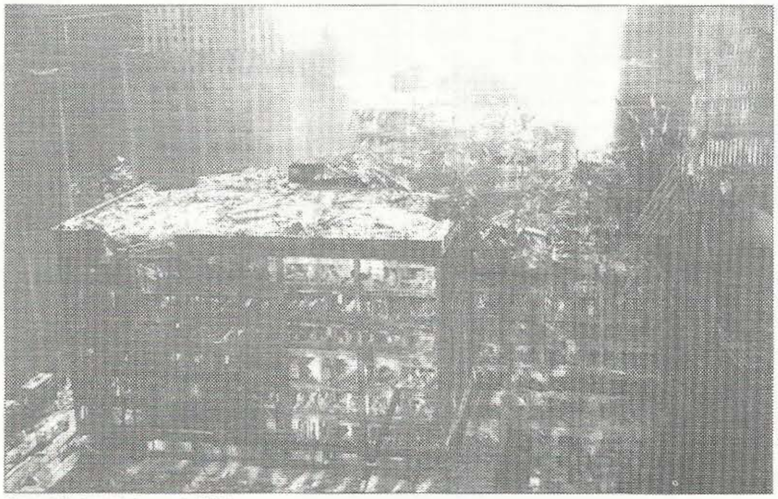


Figure 4-9 Impact damage to WTC 6

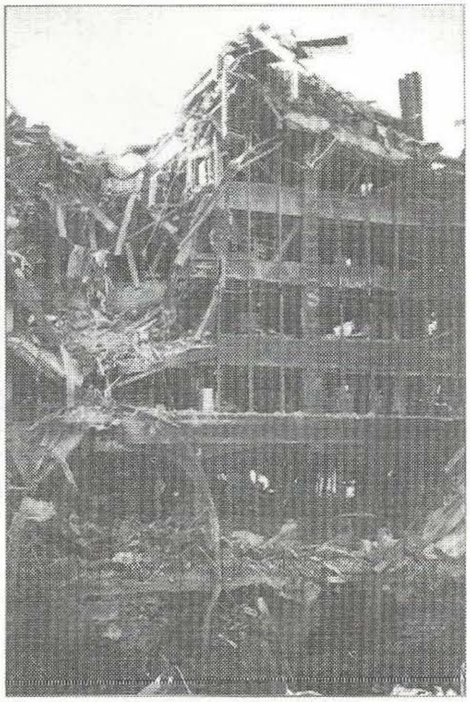


Figure 4-10
Impact damage to the exterior façade of WTC 6.

Significant impact damage to WTC 5 is shown in Figure 4-12. The damage was concentrated on the west side of the building.

4.2.2 Fire Damage

Figure 4-13 shows WTC 5 on fire. The source of ignition has not been identified. It is likely that it was due to flaming debris entering the building from WTC 1 and WTC 2. There was a complete burnout of all combustibles from the 5th floor and above. Some steel beams supporting the roof were deformed due to the heat, as illustrated in Figure 4-14, and some local buckling occurred as well. Roof tar entered the floor through the drains. There is no indication that this roof tar played a major role in the fires. One area below the roof at the 8th floor collapsed onto the 7th floor and then both onto the 6th, and so on, down to the 4th floor.

The structural damage due to the fires closely resembled that commonly observed in test assemblies exposed to the ASTM E119 Standard Fire Test. After testing, the deformed shapes of beams, girders, and columns are similar to the structural damage that occurred in these buildings. The damage also resembled the fire damage associated with the fire incident at the unsprinklered One Meridan Plaza, a steel-framed building in Philadelphia, and damage observed at experiments conducted at Cardington by the Building Research Establishment (BRE) and British Steel in 1995. These fires are discussed in greater detail in Appendix A, Section A.3.1.3.

Discrete sections of the steel framing were warped or twisted. There was no evidence of weakened connections in the areas of the building that were inspected. Some studs were missing and others were still in place in some areas, even in floor sections that had collapsed. In many deformed beams, there was no evidence of damage at openings cut into the beams, suggesting that web penetration reinforcement design worked as intended, although some localized buckling in beams and girders was observed throughout the burned-out regions.

There was significant fire damage on floors 4 through 8. On some floors, the interior had been completely gutted by fire; on others, the fire damage was severe, but there was still evidence of office partition frames and other light-gauge metal products, except for the 6th floor, which suffered near complete destruction. Even the mid-height partitions were destroyed and had collapsed throughout much of the 6th floor. This level of damage was not evident on the other floors.

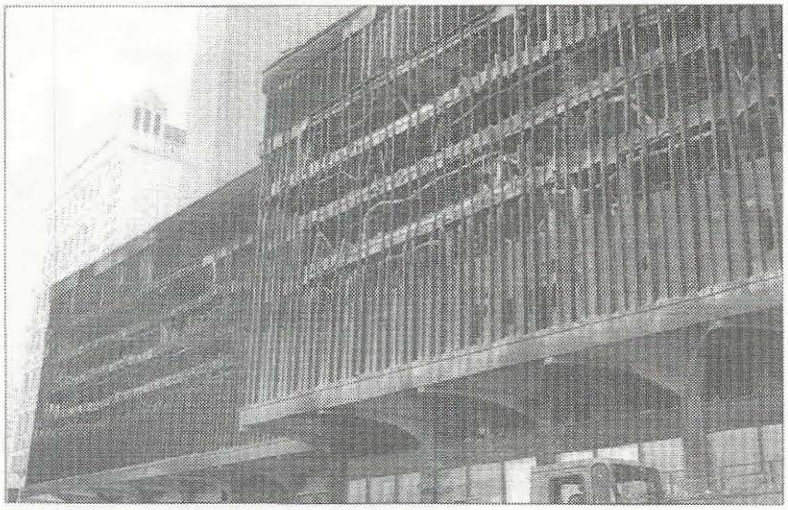


Figure 4-11 WTC 5 façade damage.

The sprinkler system appears not to have operated at all. This was evident due to the lack of water damage throughout, but especially in the lower level bookstore shown in Figure 4-15. Many sprinkler heads were damaged; some even melted and fell off the sprinkler piping in the fire areas.

As illustrated in Figure 4-16, the interior of the exit stair tower at the southwest corner was practically untouched by the fire. There were no burn marks or smoke damage in this exit tower, or on the "safe" or stairwell side of the fire door. At one location, a piece of paper was found taped to the exit stairwall just inside the fire door with no evidence of smoke or charring from fire.

4.3 Analysis of Building Performance

4.3.1 Steel and Frame Behavior

The punctures in the building envelope of WTC 5, caused by falling debris from the WTC towers, are a result that would be expected from large debris falling over a great distance. Generally, the debris punched through the roof and floor slabs and severed or otherwise damaged framing until sufficient energy had dissipated to arrest the collapse.

The debris from the towers caused damage to the outside wall steel framing of WTC 5, but this damage did not cause any additional collapse of the floors. In fact, the steel pipe façade supports (mullions) provided structural redundancy to the floor framing and redistributed some portion of the cantilevered floors to other levels.

As illustrated in Figure 4-17, there was local buckling of interior columns. This buckling was most likely due to a combination of fire-induced reductions in strength and a possible increase in stress due to restrained thermal expansion. A detailed explanation of these issues is presented in Appendix A, Section A.5.1.4.

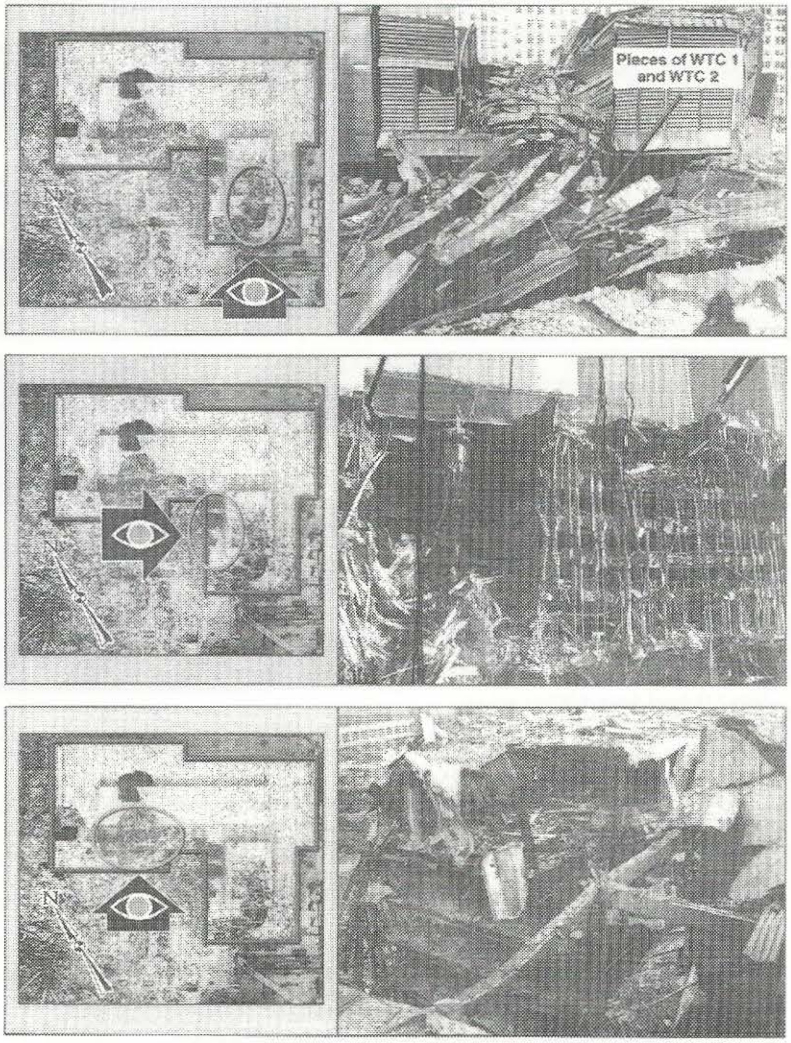

Pieces of WTC 1 and WTC 2
N
N
N

Figure 4-12 Impact damage to WTC 5.

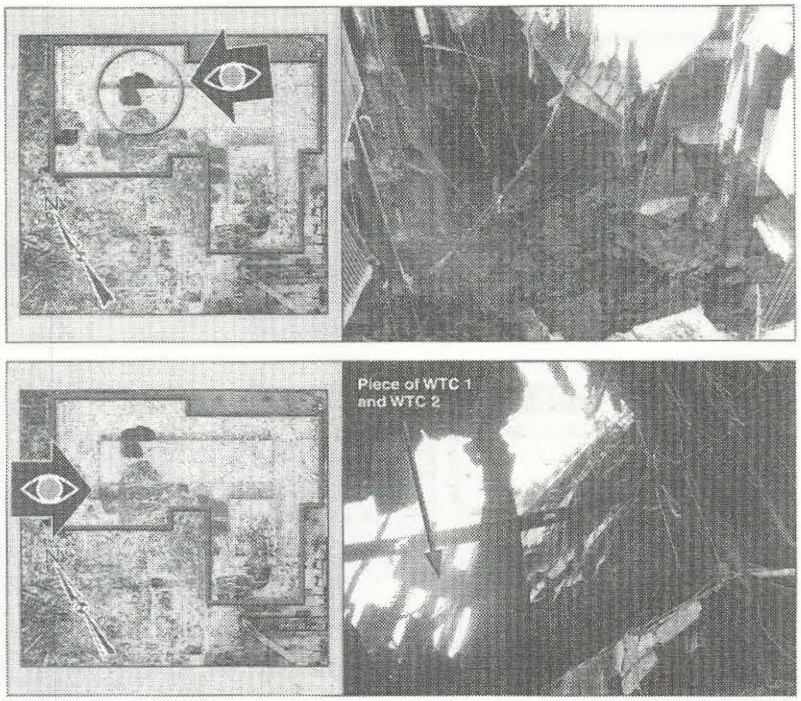


Figure 4-12 Impact damage to WTC 5 (continued).

4.3.2 WTC 5 - Local Collapse Mechanisms

Two areas in WTC 5 experienced local collapse under an intact portion of the roof. Although there was debris impact near this area, the symmetrical nature of the collapse strongly suggests that the failures were due to the uncontrolled fires. This is supported by the observation that the columns in this area remained straight and freestanding (see Figure 4-18). This local collapse appeared to have begun at the field connection where beams were connected to shop-fabricated beam stubs and column assemblies as illustrated in Figures 4-19, 4-20, and 4-21.

The structural collapse appeared to be due to a combination of excessive shear loads on bolted connections and unanticipated tensile forces resulting from catenary sagging of the beams. The existence of high shear loads, likely due to collapsing floor loads from above, was evident in many of the column-tree beam stub cantilevers that formed diagonal tension field mechanisms in the cantilever webs and plastic moments at the column, as seen in Figure 4-18.

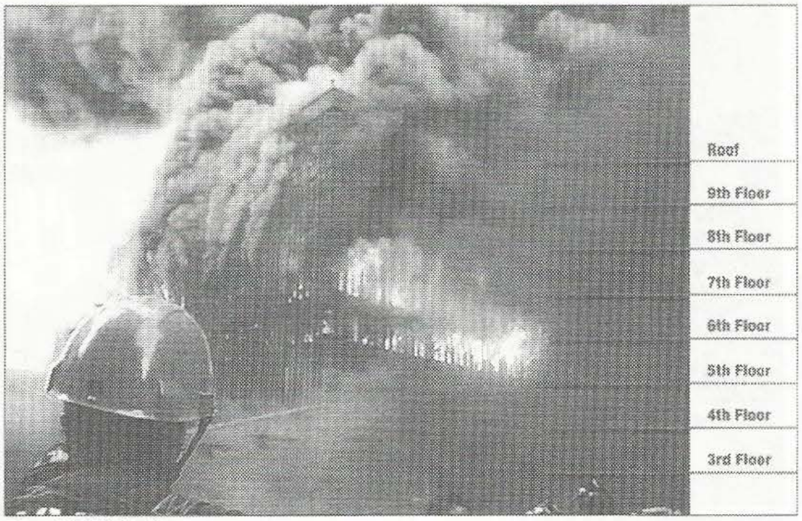

Roof
9th Floor
8th Floor
7th Floor
6th Floor
5th Floor
4th Floor
3rd Floor

Figure 4-13 WTC 5 on fire.

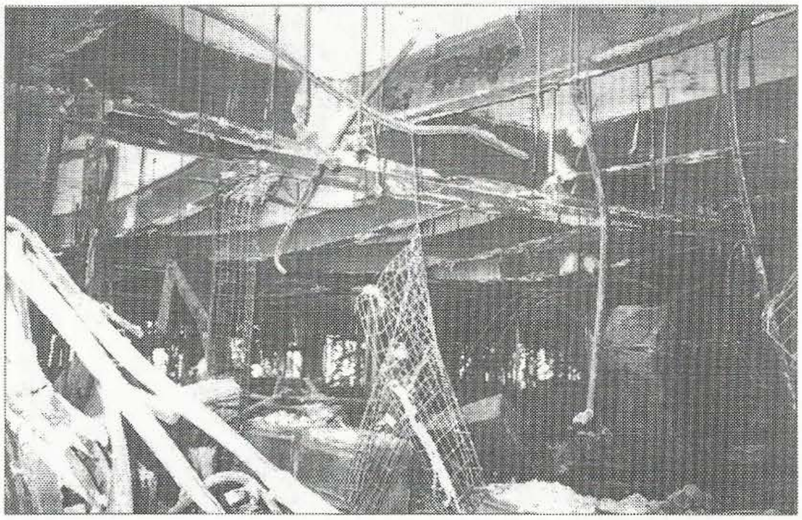


Figure 4-14 Deformed beams in WTC 5.

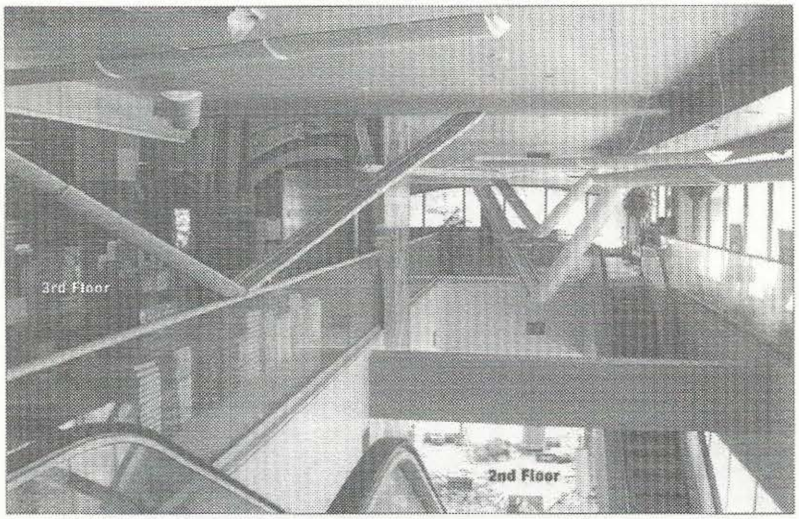


Figure 4-15 Unburned bookstore in WTC 5.

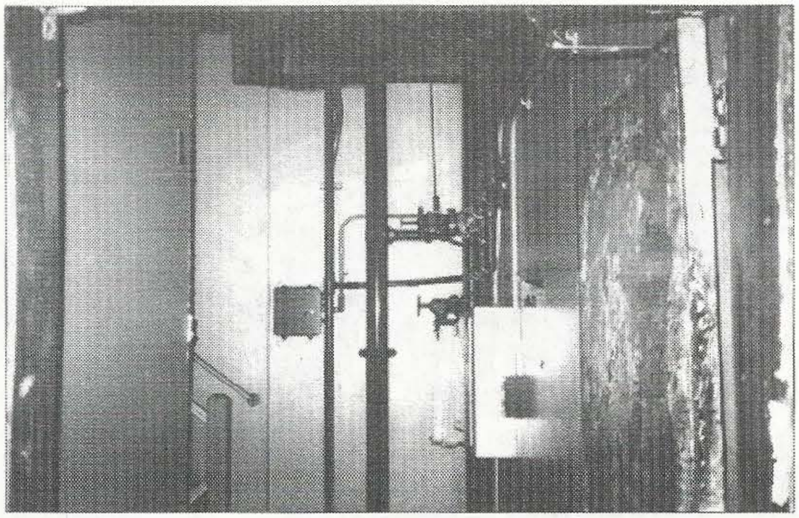


Figure 4-16 Looking through the door into the undamaged stair tower in WTC 5.

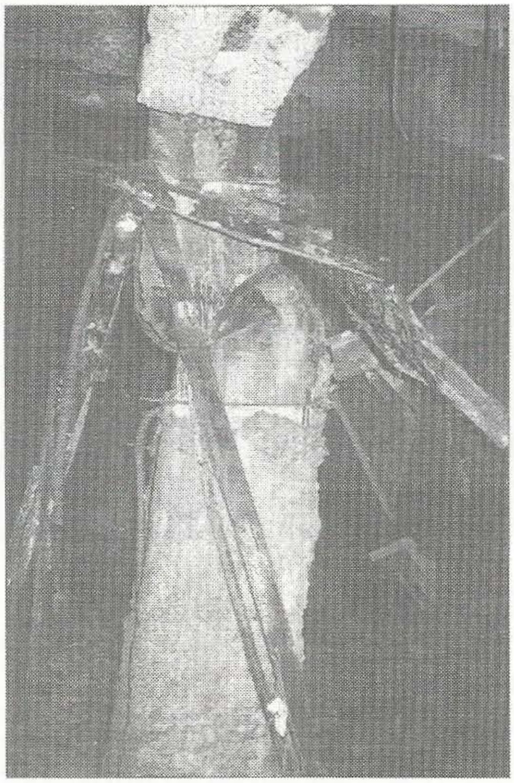


Figure 4-17
Buckled beam flange and column on the 8th floor of WTC 5 that was weakened by fire.

It is apparent that fire weakened the steel, contributing to the large shear-induced deformations observed in several of the cantilever beams. The shear failures observed at connection ends in several of the beam web samples shown in Figure 4-18 are indicative of the tensile forces that developed. The end bearing resistance of the beam web was found to be less than the double shear strength of the high-strength bolts, based on the analysis presented in Appendix B.

Steel framing connection samples were recovered from floors 6, 7, and 8 of WTC 5 with the aid of the New York Department of Design and Construction (DDC) and are described in Figure 4-22. These samples have not been analyzed and are being preserved for future study. The photographs of connection samples in Figure 4-22 indicate that the deformed structure subjected the bolted shear connection to a large tensile force. At 550 °C (1,022 °F), the ultimate resistance of the three bolts is about 45 kips. The capacity increases to approximately 90 kips at room temperature. Connection failure likely occurred between these bounds.

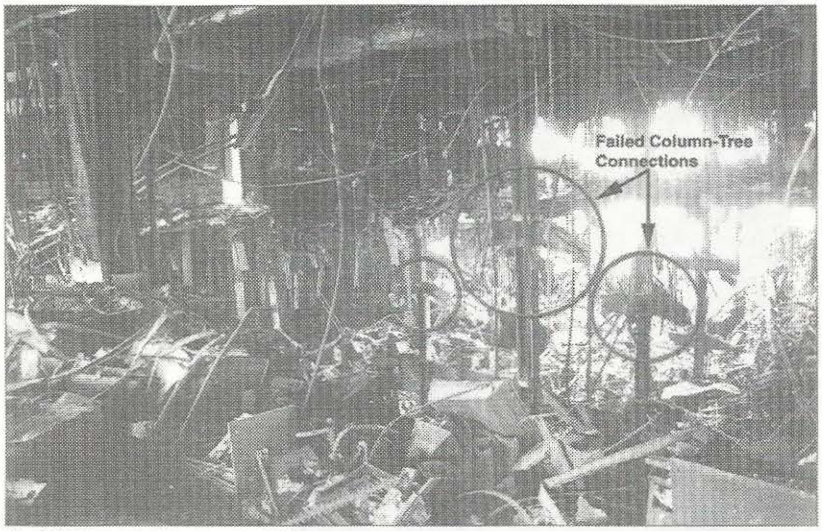


Figure 4-18 Internal collapsed area in WTC 5.

Tensile catenary action of floor framing members and their connections has been neither a design requirement nor a design consideration for most buildings. Further study of such mechanisms for member failures in fires should be conducted to determine whether current design parameters are adequate for performance under fire loads.

4.4 Observations and Findings

All three buildings suffered extensive fire and impact damage and significant partial collapse. The condition of the stairways in WTC 5 indicates that, for the duration of this fire, the fire doors and the fire protective covering on the walls performed well. There was, however, damage to the fire side of the painted fire doors, and the damage-free condition on the inside or stairwell side of those same doors indicates the doors performed as specified for the fire condition that WTC 5 experienced. These stairway enclosures were unusual for buildings that have experienced fire because they were not impacted by water from firefighting operations. In addition, the stairway doors were not opened during the fire and remained latched and closed throughout the burnout of the floors. Therefore, general conclusions regarding the effectiveness of this type of stairway construction may not be warranted.

The steel generally behaved as expected given the fire conditions in WTC 5. Many beams developed catenary action as illustrated in Figure 4-14. Some columns buckled, as shown in Figure 4-17. The one exception is the limited internal structural collapse in WTC 5. The fire-induced failure that led to this collapse was unexpected. As in the rest of the building, the steel beams were expected to deflect significantly, yet carry the load. This was not the case where the beam connections failed. The failure most likely occurred during the heating of the structure because the columns remained straight and freestanding after the collapse.

The structural redundancy provided by the exterior wall pipe columns helped to support the cantilevered floors. This was important because it kept the cantilevers from buckling near the columns as might be expected.

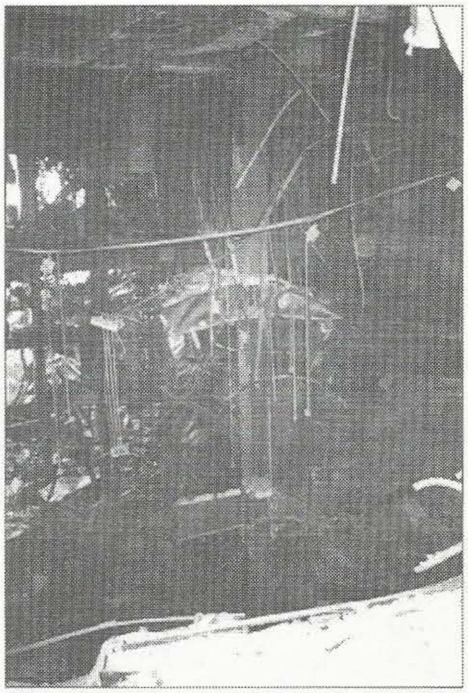


Figure 4-19
Internal collapsed area in WTC 5.

The limited structural collapse in WTC 5 due to fire impact as described in Section 4.3.2 appeared to be caused by a combination of excessive shear loads and tensile forces acting on the simple shear connections of the infill beams. The existence of high shear loads was evident in many of the column tree beam stub cantilevers that formed diagonal tension field failure mechanisms in the cantilever webs, as seen in Figure 4-19.

The end bearing resistance of the beam web was less than the double shear strength of the high-strength bolts. An increased edge distance might have prevented this collapse by increasing the connections' tensile strength. The failure most likely began on the 8th floor and progressed downward, because the 9th floor did not collapse. The 4th floor and those below remained intact.

The 7th floor framing was shop-coated. In some locations, the paint appeared to be in good condition and not discolored by the fire. Paint usually blisters and chars when heated to temperatures of about 100 °C (212 °F). This indicates that the fire protection material remained on the steel during the early phase of the fire and may have fallen off relatively later in the fire as the beams twisted, deflected, and buckled. Additional measures for proper adhesion may be required when applying spray-on fire protection to painted steel.

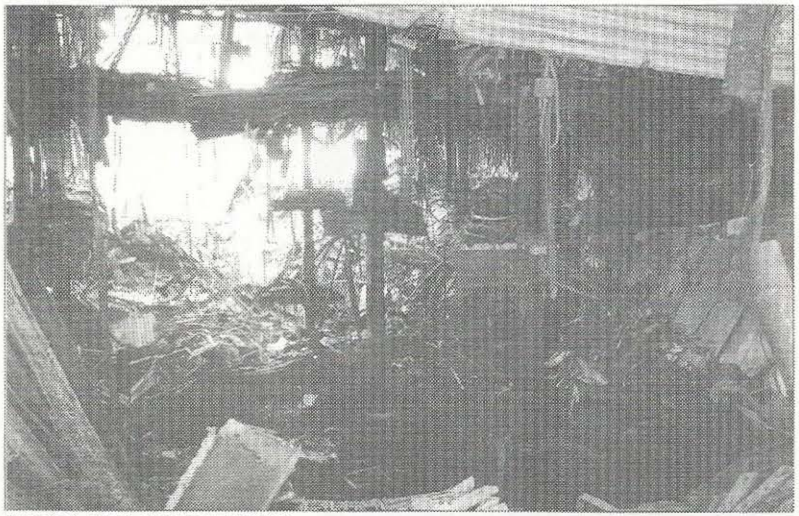


Figure 4-20 Internal collapsed area in WTC 5.

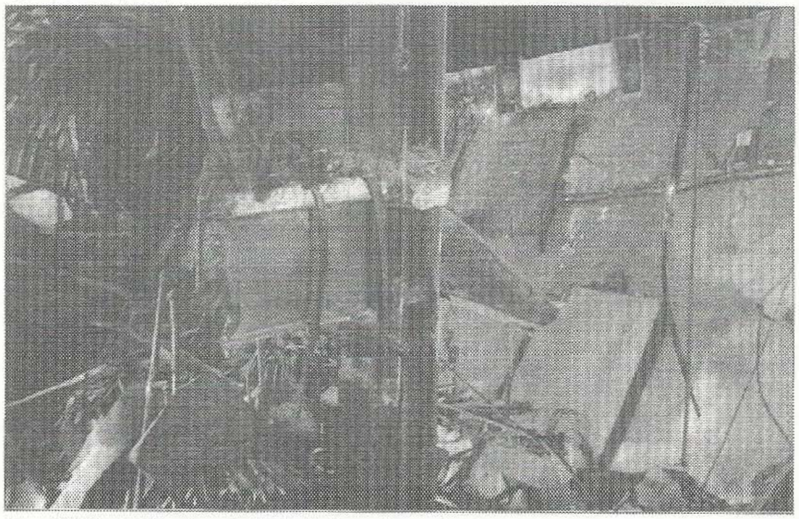
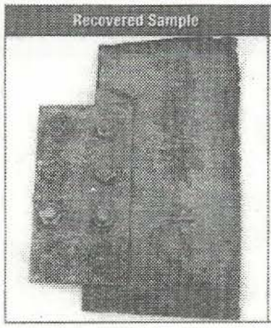
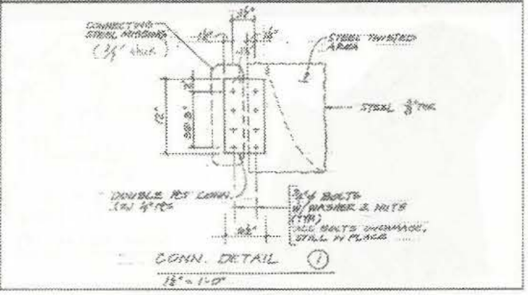


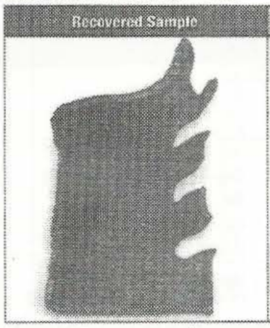
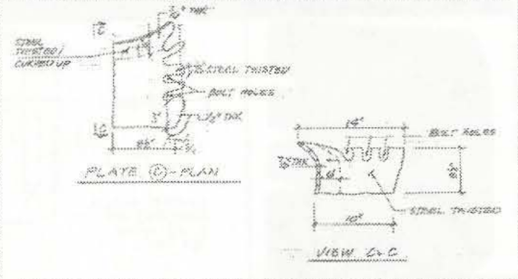
Figure 4-21 Internal collapsed area in WTC 5 with closeup of connection failure at column tree.

Recovered From: WTC 5, 8th Floor **Failure Mode:** Web tear-out at bolts

Recovered Sample	Sketch
	

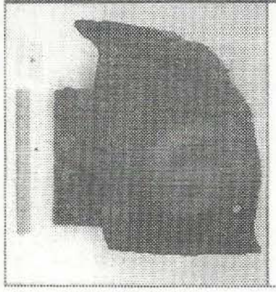
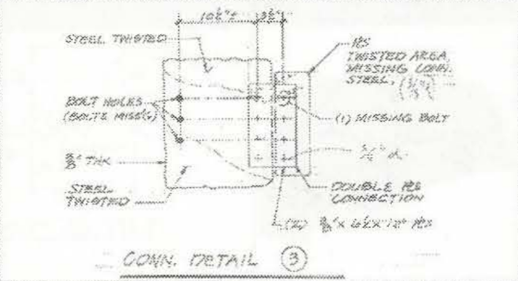
CONNECTING STEEL MISSING (3/8" thick)
STEEL TWISTED AREA
STEEL 3/8" THK
DOUBLE PL CONN. (2) 3/8" PLS
3/4" BOLTS W/ WASHER & NUTS (TYP) ALL BOLTS UNDAMAGED, STILL IN PLACE
CONN. DETAIL ①
1½" = 1'-0"

Recovered From: WTC 5, 7th Floor **Failure Mode:** Web tear-out at bolts

Recovered Sample	Sketch
	

STEEL TWISTED/ CURLED UP
STEEL TWISTED
BOLT HOLES
1/2" THK
PLATE Ⓒ - PLAN
14"
BOLT HOLES
STEEL TWISTED
10"
VIEW C-C

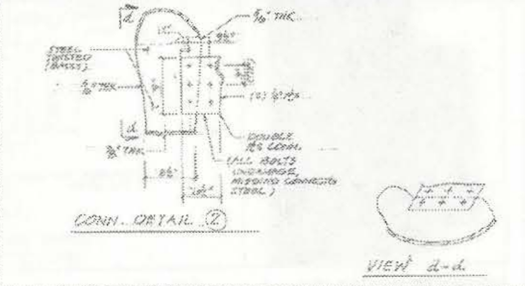
Recovered From: WTC 5, 6th Floor **Failure Mode:** Web tear-out at bolts

Recovered Sample	Sketch
	

STEEL TWISTED
PLS TWISTED AREA, MISSING CONN. STEEL
BOLT HOLES (BOLTS MISS'G)
(1) MISSING BOLT
3/4" d.
3/8" THK
STEEL TWISTED
DOUBLE PLS CONNECTION
(2) 3/8" x 6½" x 12" PLS
CONN. DETAIL ③

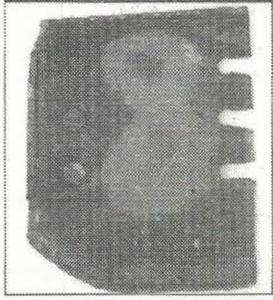
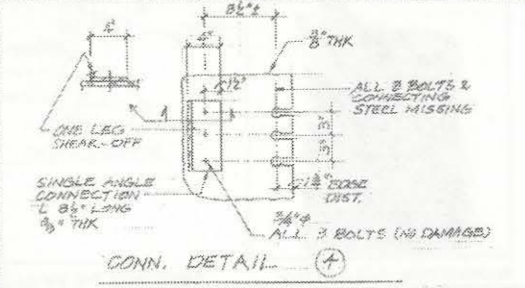
Figure 4-22 Connection samples.

Recovered From: WTC 5, 6th Floor **Failure Mode:** Web tear-out at bolts

Recovered Sample	Sketch
	

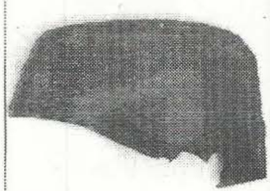
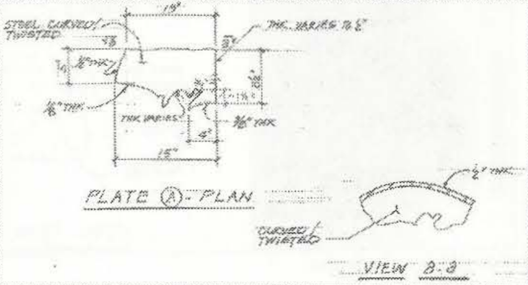
5/16" THK.
9½"
STEEL TWISTED (BASS)
5/8" THK.
(6) ¾"φs
3/8" THK.
DOUBLE ∠s CONN.
(ALL BOLTS UNDAMAGE, MISSING CONNECTG STEEL)
8½"
CONN. DETAIL ②
VIEW d-d.

Recovered From: WTC 5, 8th Floor **Failure Mode:** Plate tear-out at bolts

Recovered Sample	Sketch
	

8½"±
4"
3/8" THK
ALL 3 BOLTS & CONNECTING STEEL MISSING
ONE LEG SHEAR-OFF
SINGLE ANGLE CONNECTION
L 8½" LONG
3/8" THK
1¾" EDGE DIST.
¾"φ
ALL 3 BOLTS (NO DAMAGE)
CONN. DETAIL ④

Recovered From: WTC 5, 7th Floor **Failure Mode:** Connection web plate or splice block shear

Recovered Sample	Sketch
	

19"
STEEL CURVED/TWISTED
THK. VARIES TO ½"
½" THK
1/8" THK.
THK VARIES
3/8" THK
4"
15"
PLATE Ⓐ-PLAN
½" THK.
CURVED/TWISTED
VIEW a-a

Figure 4-22 Connection samples (continued).

Recovered From: WTC 5, Floor undetermined **Failure Mode:** Column buckling due to heat exposure

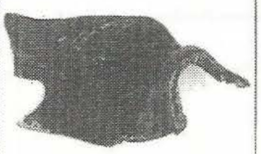
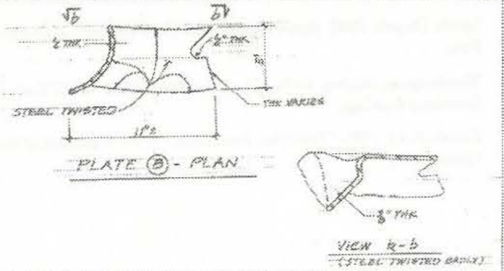
Recovered Sample	Sketch
	 b b ½ THK THK VARIES STEEL TWISTED PLATE Ⓑ - PLAN ⅜" THK VIEW b-b (STEEL TWISTED BADLY)

Figure 4-22 Connection samples (continued).

On the lower floors, the steel beams appeared to have heat damage from direct fire impact and there was little or no evidence of shop painting, indicating that fireproofing material was either missing before the fire or delaminated early in the fire exposure.

In general, the buildings responded as expected to the impact loadings. Collapse was often localized, although half of WTC 4 and most of the central part of WTC 6 suffered collapse on all floors. The damage was consistent with the observed impact load.

Reinforced web openings in steel beams performed well, as no damage or local buckling was observed at these locations.

The automatic sprinkler system did not control the fires. Some sprinkler heads fused, but there was no evidence of significant water damage, due to a lack of water. This is consistent with the lack of water damage in the bookstore on the lower level and the complete burnout of the upper floors.

4.5 Recommendations

The scope of this study and the limited time allotted prevented in-depth study of many issues that should be explored before final conclusions are reached. Additional studies of the performance of WTC 4, 5, and 6 during the events of September 11, 2001, and related building performance issues should be conducted. These include the following:

- There is insufficient understanding of the performance of connections and their adequacy under real fire exposures as discussed in Appendix A. This is an area that needs further study. The samples discussed in Section 4.3.2 should be useful in such a study.
- A determination of the combined structural and fire properties of the critical structural connections should be made to permit prediction of their behavior under overload conditions. This can be accomplished with a combination of thermal transfer modeling, structural finite element modeling (FEM), and full-scale physical testing.

4.6 References

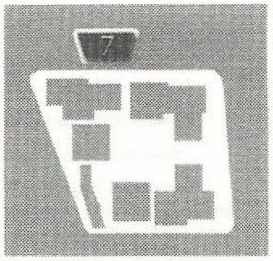
AISC. 2001. *Manual of Steel Construction.* LRFD. 3rd Edition. Chicago.

ASTM. 2000. Standard Test Methods for Fire Tests of Building Construction and Materials. ASTM E119. West Conshohocken, PA.

Smith, Dennis. 2002. *Report from Ground Zero: The Story of the Rescue Efforts at the World Trade Center.* Viking Press.

Worthington, Skilling, Helle & Jackson. 1968. "The World Trade Center, Northeast Plaza Building." Structural drawings.

Zalosh, R. G. 1995. "Explosion Protection," *SFPE Handbook of Fire Protection Engineering,* 2nd Edition. Quincy, MA.



Ramon Gilsanz
Edward M. DePaola
Christopher Marrion
Harold "Bud" Nelson

5 *WTC 7*

5.1 Introduction

WTC 7 collapsed on September 11, 2001, at 5:20 p.m. There were no known casualties due to this collapse. The performance of WTC 7 is of significant interest because it appears the collapse was due primarily to fire, rather than any impact damage from the collapsing towers. Prior to September 11, 2001, there was little, if any, record of fire-induced collapse of large fire-protected steel buildings.

The structural design and construction features of this building, potential fuel loads, fire damage, and the observed sequence of collapse are presented to provide a better understanding of what may have happened. However, confirmation will require additional study and analysis. Information about the structural design and construction features and the observed sequence of events is based upon a review of structural drawings, photographs, videos, eyewitness reports, and a 1986 article about the construction features of WTC 7 (Salvarinas 1986). In addition, the following information and data were obtained from the indicated sources:

- Annotated floor plans and riser diagrams of the emergency generators and related diesel oil tanks and distribution systems (Silverstein Properties 2002)
- Engineering explanation of the emergency generators and related diesel oil tanks and distribution systems (Flack and Kurtz, Inc. 2002)
- Information on the continuity of power to WTC 7 (Davidowitz 2002)
- Summary of diesel oil recovery and spillage (Rommel 2002)
- Information on WTC 7 fireproofing (Lombardi 2002)
- Information on the New York City Office of Emergency Management (OEM) tanks at WTC 7 (Odermatt 2002)

The 47-story office building had 1,868,000 square feet of office space. The top 40 stories of the building (floors 8 to 47) were office type occupancies. Table 5.1 lists the larger tenants of WTC 7. WTC 7 was completed in 1987 by a development team composed of the following parties:

- Owner/Developer: Seven World Trade Company, Silverstein Development Corporation, General Partner
- Construction Manager: Tishman Construction Corporation of New York
- Design Architect: Emery Roth & Sons, P.C.

- Structural Consultant: The Office of Irwin G. Cantor, P.C.
- Mechanical/Electrical Consultant: Syska & Hennessy, P.C.
- Structural Consultant (Con Ed Substation): Leslie E. Robertson Associates

As shown in Figure 1-1 (WTC site map in Chapter 1), WTC 7 was located north of the main WTC complex, across Vesey Street, and was linked to the WTC Plaza by two pedestrian bridges: the large Plaza bridge and a smaller, glass-enclosed pedestrian bridge. The bridges spanned 95 feet across Vesey Street, connecting the Plaza and the 3rd floor of WTC 7. In addition to the office occupancies, WTC 7 also contained an electrical substation, and the WTC Complex shipping ramp, as shown in Figure 5-1.

Table 5.1 WTC 7 Tenants

Floor	Tenant
46-47	Mechanical Floors
28-45	Salomon Smith Barney (SSB)
26-27	Standard Chartered Bank
25	Internal Revenue Service (IRS)
	Department of Defense (DOD)
	Central Intelligence Agency (CIA)
24	Internal Revenue Service (IRS)
23	Office of Emergency Management (OEM)
22	Federal Home Loan Bank of New York
21	First State Management Group
19-21	ITT Hartford Insurance Group
19	National Association of Insurance Commissioners (NAIC) Securities Valuation Office
18	Equal Employment Opportunity Commission (EEOC)
14-17	Vacant
13	Provident Financial Management
11-13	Securities and Exchange Commission
9-10	U.S. Secret Service
7-8	American Express Bank International
7 part	OEM generators and day tank
6	Switchgear, storage
5	Switchgear, generators, transformers
4	Upper level of 3rd floor lobby, switchgear
3	Lobby, SSB Conference Center, rentable space, management offices
2	Open to 1st floor lobby, transformer vault upper level, upper level switchgear
1	Lobby, loading docks, existing Con Ed transformer vaults, fuel storage, lower level switchgear

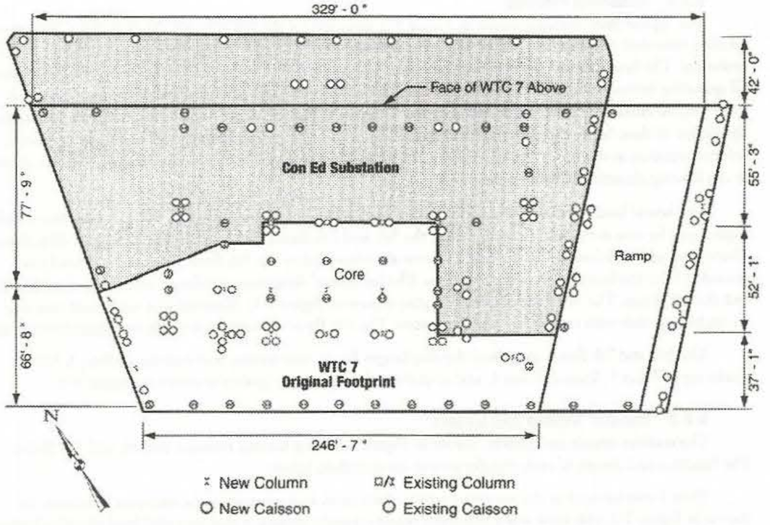


Figure 5-1 Foundation plan – WTC 7.

The substation and shipping ramp occupied major portions of the WTC 7 site. The substation was built prior to the office tower, supplied electrical power to lower Manhattan, and covered approximately half the site. The shipping ramp (5,200 square feet in area, approximately 10 percent of the WTC 7 site) was used by the entire WTC complex.

5.2 Structural Description

5.2.1 Foundations

With the development of an office tower in mind, the Port Authority of New York and New Jersey (hereafter referred to as the Port Authority) installed caissons intended for future construction. However, Seven World Trade Company, Silverstein Development Corporation, General Partner, decided to construct a building much larger in both height and floor area. The designers combined the existing caissons inside the substation with new caissons inside and outside the substation to create the foundation for WTC 7. Figure 5-1 shows the location of pre-existing caissons built when the Con Ed substation was constructed along with new caissons that were installed for the support of the building. The discrepancy in the column locations between the substation and the office tower required transfers to carry loads from the office tower to the substation and finally into the foundation. Old and new caissons, as well as old and new columns, also can be seen in the foundation plan shown in Figure 5-1.

5.2.2 Structural Framing

The typical floor framing shown in Figure 5-2 was used for the 8th through the 45th floors. The gravity framing consisted of composite beams (typically W16x26 and W24x55) that spanned from the core to the perimeter. The floor slab was an electrified composite 3-inch metal deck with 2-1/2-inch normal-weight concrete fill spanning between the steel beams. Below the 8th floor, floors generally consisted of formed slabs with some limited areas of concrete-filled metal decks. There were numerous gravity column transfers, the more significant of these being three interior gravity column transfers between floors 5 to 7 and eight cantilever column transfers in the north elevation at the 7th floor. The column transfers in the exterior walls are shown in the bracing elevations (Figure 5-3).

The lateral load resisting system consisted of four perimeter moment frames, one at each exterior wall, augmented by two-story belt trusses between the 5th and 7th floors and between the 22nd and 24th floors. There were additional trusses at the east and west elevations below the 7th floor. An interior braced core extended from the foundation to the 7th floor. The horizontal shear was transferred into the core at the 5th and the 7th floors. The 5th floor diaphragm (plan shown in Figure 5-4) consisted of a reinforced concrete 14-inch-thick slab with embedded steel T-sections. The 7th floor was an 8-inch-thick reinforced concrete slab.

The 5th and 7th floors contained the diaphragm floors, belt trusses, and transfer girders. A 3-D rendering of Truss 1, Truss 2, Truss 3, and several cantilever transfer girders is shown in Figure 5-5.

5.2.3 Transfer Trusses and Girders

The transfer trusses and girders, shown in Figure 5-6, were located between the 5th and 7th floors. The function and design of each transfer system are described below.

Truss 1 was situated in the northeast sector of the core, and spanned in the east-west direction. As shown in Figure 5-7, this truss was a two-story double transfer structure that provided load transfers between nonconcentric columns above the 7th floor to an existing column and girder at the 5th floor. The girder then provided a second load transfer to an additional two columns. The 7th floor column supported 41 floors and part of the east mechanical penthouse. Its load was transferred through the triangular truss into a column

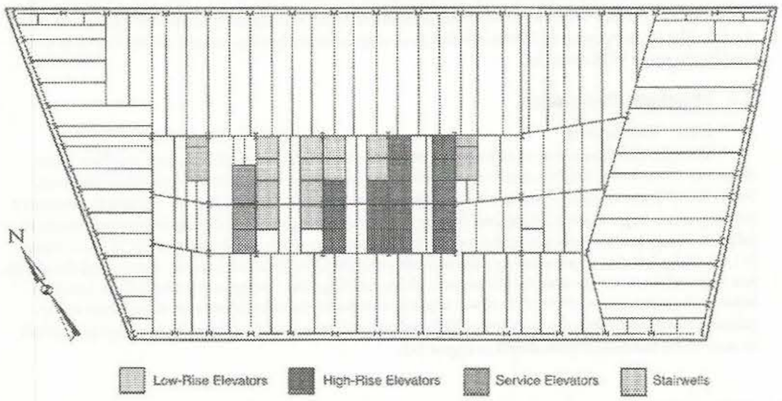
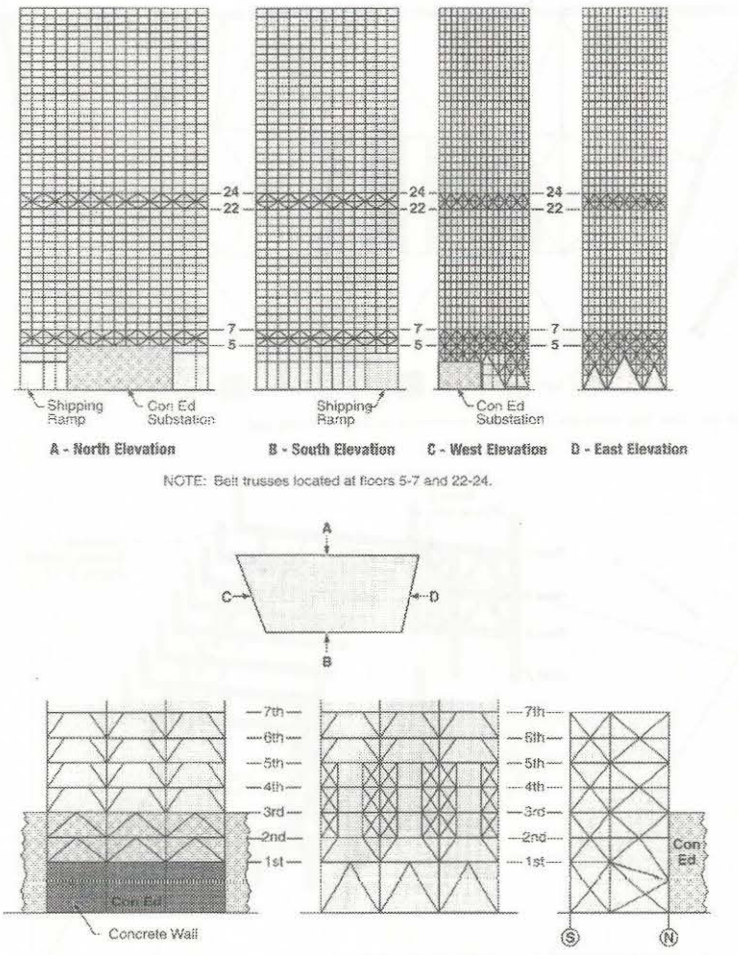


Figure 5-2 Plan view of typical floor framing for the 8th through 45th floors.


24
22
7
5
Shipping Ramp
Con Ed Substation
Shipping Ramp
Con Ed Substation
A
B
C
D
7th
6th
5th
4th
3rd
2nd
1st
Con Ed
Concrete Wall
Con Ed
S
N

A - North Elevation B - South Elevation C - West Elevation D - East Elevation

NOTE: Belt trusses located at floors 5-7 and 22-24.

E - North Core Elevation F - South Core Elevation G - Transverse Core Elevations

Figure 5-3 Elevations of building and core area.

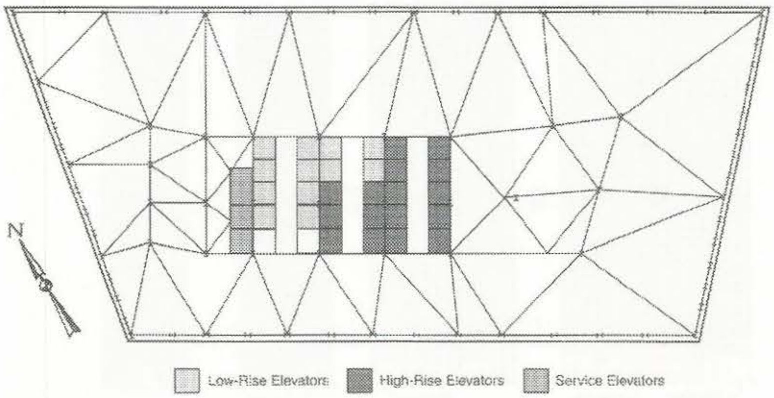
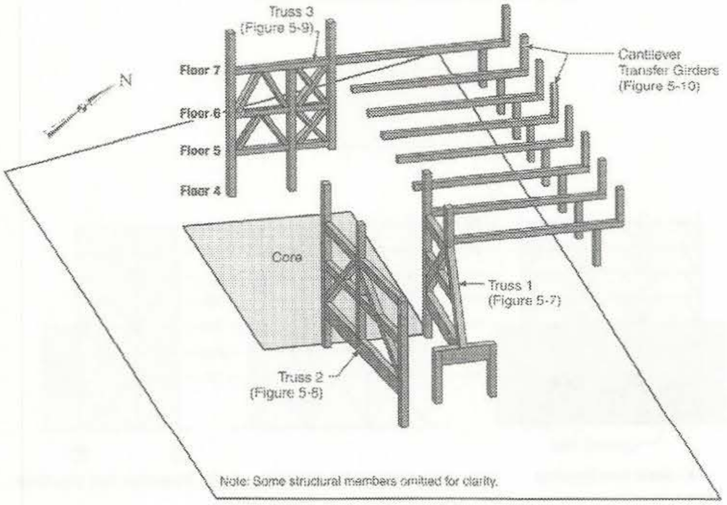

N
Low-Rise Elevators
High-Rise Elevators
Service Elevators

Figure 5-4 Fifth floor diaphragm plan showing T-sections embedded in 14-inch slab.


Truss 3
(Figure 5-9)
N
Floor 7
Floor 6
Floor 5
Floor 4
Cantilever
Transfer Girders
(Figure 5-10)
Core
Truss 1
(Figure 5-7)
Truss 2
(Figure 5-8)

Note: Some structural members omitted for clarity.

Figure 5-5 3-D diagram showing relation of trusses and transfer girders.

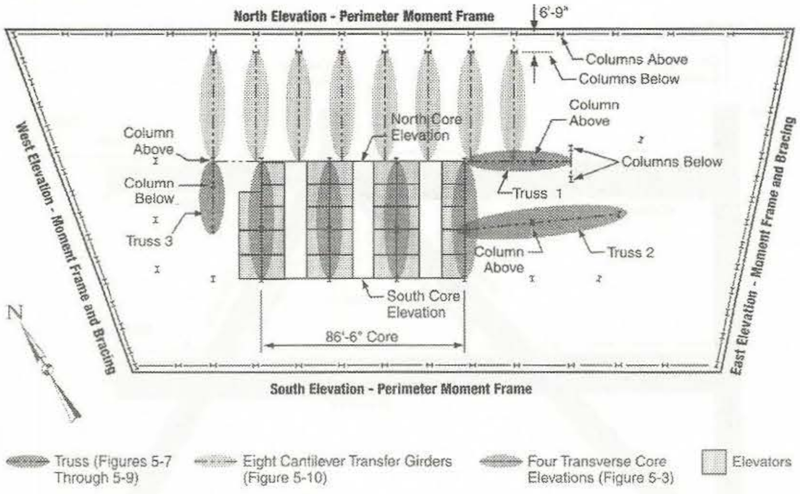

North Elevation - Perimeter Moment Frame
6'-9"
Columns Above
Columns Below
Column Above
North Core Elevation
Column Above
Columns Below
Column Below
Truss 1
Truss 3
Column Above
Truss 2
West Elevation - Moment Frame and Bracing
East Elevation - Moment Frame and Bracing
South Core Elevation
86'-6" Core
N
South Elevation - Perimeter Moment Frame
Truss (Figures 5-7 Through 5-9)
Eight Cantilever Transfer Girders (Figure 5-10)
Four Transverse Core Elevations (Figure 5-3)
Elevators

Figure 5-6 Seventh floor plan showing locations of transfer trusses and girders.

located above an existing substation column and girder at the 5th floor. The 36.5-ton built-up double web girder spanned in the north-south direction between two new columns that started at the foundation and terminated at the 7th floor. The truss diagonals were W14 shapes and the horizontal tie was a 22-ton, built-up shape.

Truss 2 was a single transfer located south of Truss 1. As shown in Figure 5-8, Truss 2 transferred the column load from the 7th floor through a triangular truss into two existing columns at the 5th floor. Large gusset plates were provided at the connection between the diagonals, the columns, and the horizontal tie. The diagonals and the built-up horizontal tie were field-welded.

Truss 3 was a cantilevered two-story transfer structure in the north-south direction between the 5th and 7th floors at the western end of the core area. As shown in Figure 5-9, Truss 3 transferred the loads between columns. The upper columns carried 41 floors of load and were cantilevered to the north of the column that went from the foundation to the 7th floor.

The cantilever transfer girders, shown in Figure 5-10, spanned between the core and the north elevation at the 7th floor. There were eight transfer girders to redirect the load of the building above the 7th floor into the columns that went through the Con Ed substation. These girders cantilevered 6 feet 9 inches between the substation and the north façade of the building above. The girders extended an additional 46 feet to the core. The two transfer girders at the east end of the building were connected to Truss 1, creating a double transfer. The girders varied in depth from 9 feet at the north end, to a tapered portion in the middle, and to 4 feet 6 inches at the southern section closest to the core. Each transfer girder weighed approximately 52 tons. At the north wall, between the 7th and 5th floors, transferred columns were also part of the belt truss that circled the building as part of the lateral-load-resisting system and acted as a transfer for the columns above the shipping ramp.

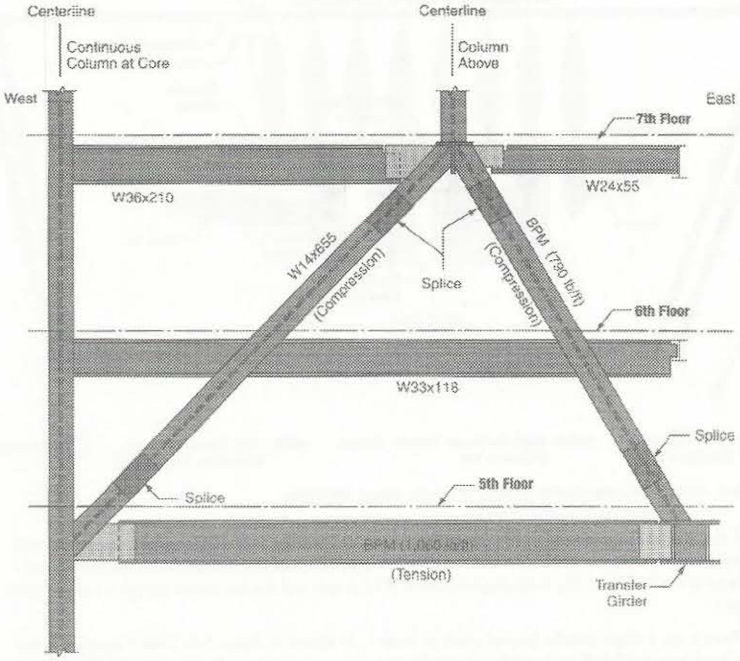

Centerline
Continuous
Column at Core
Centerline
Column
Above
West
East
7th Floor
W36x210
W24x55
W14x655
(Compression)
Splice
BPM (730 lb/ft)
(Compression)
6th Floor
W33x118
Splice
5th Floor
Splice
BPM (1,060 lb/ft)
(Tension)
Transfer
Girder

Figure 5-7 Truss 1 detail. (BPM = built-up plate member.)

5.2.4 Connections

A variety of framing connections were used. Seated beam connections were used between the exterior columns and the floor beams. Single-plate shear connections were generally used at beam-to-beam connections. Double-angle connections were provided between some beam and end-plate connections at beam-to-interior columns. Floor-framing connections used 7/8-inch-diameter ASTM A325 bolts; connections for bracing, moment frames, and column splices used 1-inch diameter ASTM A490 bolts.

Along the east and west elevations, center-to-center column spacing was typically less than 10 feet. Column trees were used at these locations. A column tree is a shop-fabricated column assembly with beam stubs shop-welded to the column flanges. The field connections were made at the end of the stubs at the center of the span between columns. One-sided lap plates were used for both flange and web connections.

Along the north and south elevations, and within the core up to the 7th floor, the spans were approximately 28 feet. At these locations, traditional moment frame construction was used. Top and bottom flange plates, as well as one-sided web shear plates, were shop-welded to column flanges. The beams were then field-bolted into the connection.

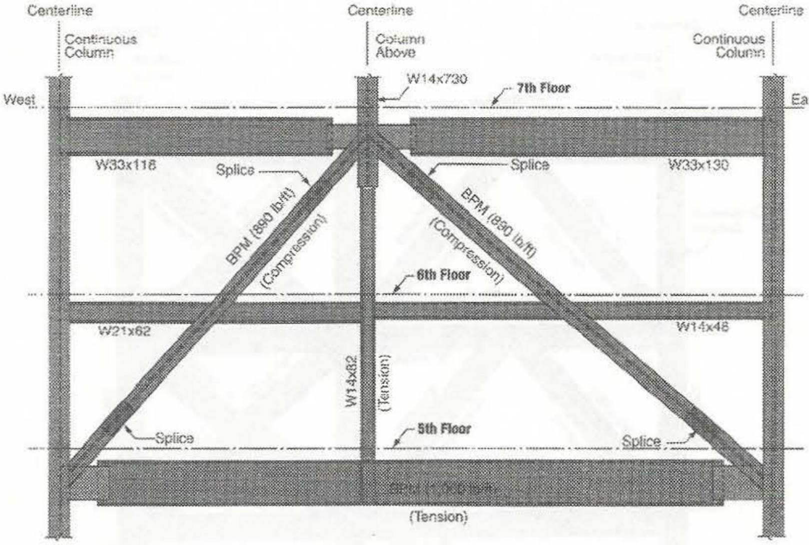

Centerline
Continuous Column
Centerline
Column Above
Centerline
Continuous Column
W14x730
7th Floor
West
East
W33x118
Splice
Splice
W33x130
BPM (890 lb/ft)
(Compression)
BPM (890 lb/ft)
(Compression)
6th Floor
W21x62
W14x48
W14x82
(Tension)
Splice
5th Floor
Splice
BPM (1,000 lb/ft)
(Tension)

Figure 5-8 Truss 2 detail. (BPM = built-up plate member.)

The majority of column splices were bolted according to American Institute of Steel Construction (AISC) details. They were located 3 feet 6 inches above the floor and were not designed to accommodate tensile forces. Columns below the 7th floor were often "jumbo" shapes (W14x455 to W14x730) or built-up jumbo box shapes with plates up to 10 inches thick welded from flange to flange, parallel to the web, to provide the necessary section properties. For these massive columns, either the upper shaft was beveled to be field-welded or side plates were shop-welded to the lower shaft and field-welded to the upper shaft once the column was erected and plumb.

The majority of the bracing members were two channels or two T-sections connected to the structure by a welded gusset plate. A single wide flange cross-section was also used. These members were connected with web and flange plates, similar to those used in the moment frames. Some of the bracing members on the east and west sides of the building were as large as the jumbo column sections. Large connection plates were sandwiched to each side of these large braces, beams, and columns at their junctions. Bolts attached all the components to each other at these joints.

The granite façade panels were manufactured off site and were supported by individual trusses. Each panel had a single vertical/gravity connection and top and bottom lateral/wind connections to transmit these forces back to the base building. Horizontal panel adjustments could be accommodated within the panel itself. The building columns had welded angles and channels that provided horizontal and lateral support. The top of the panel was connected to the angle, and the bottom of the panel was connected to the channel. These steel-panel connections had vertically slotted holes for vertical adjustment.

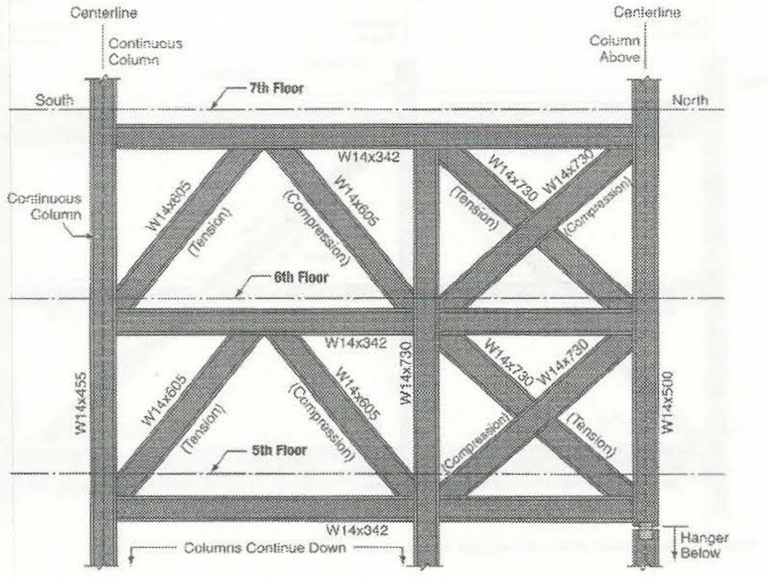

Centerline
Continuous Column
Centerline
Column Above
South
North
7th Floor
6th Floor
5th Floor
Continuous Column
W14x342
W14x605
(Tension)
W14x605
(Compression)
W14x730
W14x730
(Tension)
(Compression)
W14x342
W14x605
(Tension)
W14x605
(Compression)
W14x730
W14x730
W14x730
(Compression)
(Tension)
W14x455
W14x500
W14x342
Columns Continue Down
Hanger Below

Figure 5-9 Truss 3 detail.

5.3 Fire Protection Systems

5.3.1 Egress Systems

There were two main exit stairways in WTC 7. Stairway 1 was located on the west side, and Stairway 2 was located on the east side within the central core. Both exit stairways discharged directly to the exterior at ground level and were approximately 4 feet 10 inches wide. The stairways were built of fire-rated construction using gypsum wallboard. Subsequent to the 1993 bombing incident at the WTC, battery-operated emergency lighting was provided in the stairways and photoluminescent paint was placed on the edge of the stair treads to facilitate emergency egress. In addition to the battery-powered lighting, the stairs also had emergency system lighting powered by the generators.

Twenty-eight passenger elevators and three service elevators served the various levels of WTC 7. Occupants using the elevators would typically discharge at the third level and either exit through the Lobby to bridges bringing them over to the WTC Plaza, or proceed down the escalators to grade level.

5.3.2 Detection and Alarm

Smoke detectors were located in telecommunications, electrical, and communications closets, as well as inside the HVAC system ducts, in the mechanical rooms, and in all elevator lobbies. Manual pull stations were provided at the entrances to stairways and at each of the exits. Speakers for voice evacuation

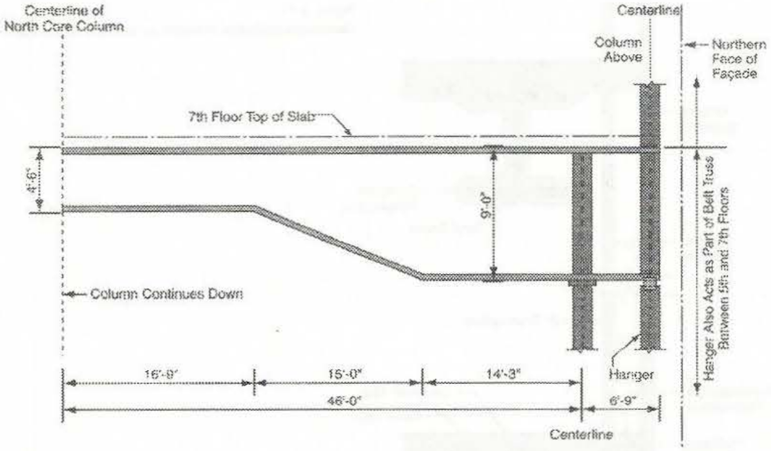

Centerline of
North Core Column
Centerline
Column
Above
Northern
Face of
Façade
7th Floor Top of Slab
4'-6"
9'-0"
Column Continues Down
Hanger Also Acts as Part of Belt Truss
Between 5th and 7th Floors
16'-9"
15'-0"
14'-3"
46'-0"
Hanger
6'-9"
Centerline

Figure 5-10 Cantilever transfer girder detail.

announcements were located throughout the building and were activated manually at the Fire Control Center (FCC). Strobes were provided and were activated automatically upon detection of smoke, water flow, or initiation of a manual pull station. Monitoring of the fire-alarm control panel for WTC 7 was provided independently at a central station. In addition to the emergency generators, the existing uninterruptible power supply (UPS) provided 4 hours of full operation for the fire-alarm system and 12 hours of standby operation. The floor contained a combination of area smoke and heat detectors.

5.3.3 Compartmentalization

Concrete floor slabs provided vertical compartmentalization to limit fire and smoke spread between floors (see Figure 5-11). Architectural drawings indicate that the space between the edge of the concrete floor slab and curtain wall, which ranged from 2 to 10 inches, was to be filled with firestopping material.

A zoned smoke control system was present in WTC 7. This system was designed to pressurize the floors above and below the floor of alarm, and exhaust the floor of alarm to limit smoke and heat spread.

The fireproofing material used to protect the structural members has been identified by Silverstein Properties as "Monokote." The Port Authority informed the BPS Team that New York City Building Code Construction Classification 1B (2-hour rating for beams, girders, trusses, and 3-hour rating for columns) was specified for WTC 7 in accordance with the architectural specifications on the construction notes drawing PA-O. According to the Port Authority, the construction notes on drawing PA-O also specified the following:

- Exterior wall columns (columns engaged in masonry walls) shall be fireproofed on the exterior side with 2-inch solid gypsum, 3-inch hollow gypsum, 2-inch concrete or spray-on fireproofing.

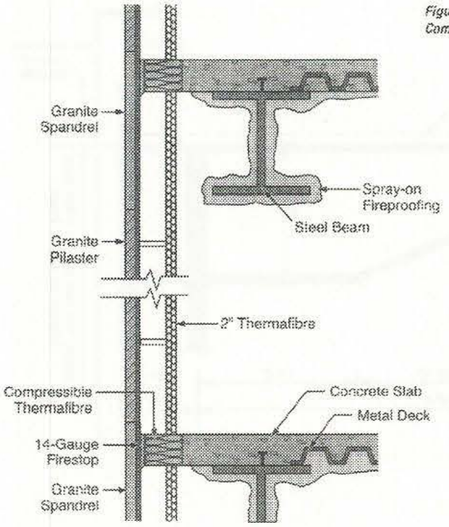


Figure 5-11
Compartmentalization provided by concrete floor slabs.

- Interior columns shall be fireproofed with materials and have rating conforming with Section C26-313.3 (27-269 current section).
- Beams and girders shall be fireproofed with 2-inch grade Portland cement concrete, Gritcrete, or srpay-on fireproofing or other materials rendering a 2-hour fire rating.

The Port Authority stated that it believed the thickness of the spray-on fireproofing was determined by the fireproofing trade for the specific structural sections used, based on the Underwriters Laboratories formula for modifications, which were reviewed by the Architect/Engineer of Record during the shop drawing submittal. Spray-on fireproofing, as required by the code, was also listed on the drawing as an item subject to controlled inspections, in accordance with Section C26-106.3 (27-132 current section). The Architect/Engineer of Record was responsible for ensuring that the proper thickness was applied. The Port Authority had extended its fireproofing inspection program to this building.

5.3.4 Suppression Systems

The primary water supply appears to have been provided by a dedicated fire yard main that looped around most of the complex. This yard main was supplied directly from the municipal water supply. Fire department connections were located on the south and west sides.

WTC 7 was a sprinklered building. However, only the core spaces on the 5th floor were sprinkler protected, and none of the electrical equipment rooms in the building were sprinkler protected. The sprinkler protection was of "light hazard" design. The sprinkler system on most floors was a looped system fed by a riser located in Stairway 2. The loading dock was protected with a dry-pipe sprinkler system. The area of the fuel tank for OEM had a special fire detection and suppression system.

The Fire Pump Room was located on the ground floor in the southwest corner of the building and contained an automatic (as well as a manual) fire pump. There were two Fire Department of New York connections in the southwest quadrant - one on the south façade and one on the west façade.

Each stairway had standpipes in it. At each floor in each stairway, there was a 2-1/2-inch outlet with a 1-1/2-inch hose (with a 3/4-inch nozzle). In addition, the east side of each floor also had a supplemental fire hose cabinet. Primary water supply to the standpipe system came from a yard main, which was fed from the municipal water supply.

5.3.5 Power

Power to WTC 7 entered at 13,800 volts (V), was stepped down to 480/277 V by silicone oil-filled transformers in individual masonry vaults on the 5th floor, and was distributed throughout the building. On each floor, one of the 277 legs was tapped and stepped down to supply single-phase 120-V branch circuits. The main system had ground fault protection. Emergency power generators were located on various levels and provided a secondary power supply to tenants. This equipment supplied backup power for communications equipment, elevators, emergency lighting in corridors and stairwells, and fire pumps. Emergency lighting units in the exit stairways, elevator lobbies, and elevator cabs were equipped with individual backup batteries.

The tanks that provided fuel for the emergency generators were located in the building. The Silverstein and Salomon Smith Barney (SSB) fuel tanks were underground below the loading dock. The OEM tank was on the ground floor on a fire-rated steel platform within a 4-hour fire-rated enclosure. SSB had supply and return piping to the emergency generators made from a 2-1/2-inch double-wall steel pipe with a 4-inch outside diameter. The SSB fuel oil riser was single-wall pipe with a masonry shaft. Only the horizontal piping on the 5th floor was a double-wall pipe within a pipe. The pumps located at the ground floor could supply 75 gallons per minute (gpm). A 3-gpm fuel supply rate was needed for each of the nine 1,725-kilowatt (kW) generators located on the 5th floor. One gallon would be consumed and the other 2 gallons would continue to circulate through the system. The SSB fuel oil pumps were provided with UPS power supported by both base building emergency power and SSB standby power. The volume between the inner and outer pipes was designed to contain a leak from the inner pressurized pipe and direct that fuel oil to a containment vessel. Upon detection of fuel oil in the containment vessel, the fuel oil pumps automatically de-energized. The SSB fuel oil pumps and distribution piping were dedicated to the SSB generator plant. The base building life safety generators and OEM generators had their own dedicated fuel oil pumps and piping. The Silverstein generators consisted of two 900-kW units, which were also located on the 5th floor, and supplied by a 275-gallon day tank. Other characteristics of the design or controls for the fuel system for the generators are unknown.

5.4 Building Loads

The degree of impact damage to the south façade could not be documented. However, damage was evident from review of photographs and video records. The number of fires observed after the collapse of WTC 1 also makes it likely that debris impact damage occurred in a number of locations.

An array of fuels typically associated with offices was distributed throughout much of the building. In addition, WTC 7 contained 10 transformers at street level, 12 transformers on the 5th floor, and 2 dry transformers on the 7th floor. The Con Ed substation contained (outside the building footprint) eight 30-foot-wide transformers that supplied 13-kilovoltampere (kVA) power to the 6th floor of the building. Fuel oil (ranging from diesel to #4) was provided for the generators serving OEM, SSB, Silverstein Properties, and the U.S. Secret Service. Table 5.2 shows where the generators, fuel tanks, pumps, and risers were located for the various occupants. There was also a Con Ed 4-inch-diameter gas line with 0.25 pounds per square inch (psi) (low) pressure going into WTC 7 for cooking purposes. Early news reports had indicated that a high-pressure, 24-inch gas main was located in the vicinity of the building; however, this proved not to be true.

Table 5.2 WTC 7 Fuel Distribution Systems

	Storage Tanks	Pumps	Riser	Day Tank	Generators
OEM	Used Silverstein tank to fill day tanks	Ground floor: 33.3 gpm	Located in shaft in west elevator bank	275-gallon tank on 7th floor; one 6,000-gallon tank located between low-rise elevators in east elevator shaft between 2nd and 3rd floors	Three 500-kW on 7th floor on south side
Salomon Smith Barney	Two 6,000-gallon tanks under loading dock on ground level	in Fire Pump Room, west side of ground floor; 75 gpm	Located in shaft in mechanical rooms on southwest corner of building	None: pressurized recirculating loop with 2.5-inch-inside-diameter double-wall supply and return steel pipe on 5th floor	Nine 1,725-kW on 5th floor, six on north side, three in southwest corner
Silverstein Properties	Two 12,000-gallon tanks under loading dock on ground level	Between elevator shafts on west side of ground floor; 4.4 gpm	Located in shaft in west elevator bank	275-gallon tank on 5th floor	Two 900-kW on 5th floor in southwest corner
U.S. Secret Service	Used Silverstein tank	Used Silverstein pumps	Located in shaft in west elevator bank	Approximately 50- to 100-gallon tank under generator on 9th floor	9th floor
American Express	Day tank only	None	None	275-gallon tank on 8th floor on west side next to exterior wall	8th floor

As described in Section 5.6.2, the sequence of the WTC 7 collapse is consistent with an initial failure that occurred internally in the lower floors on the east side of the building. The interest in fuel oil is therefore directed at the parts of the fuel oil distribution system having the potential of supporting a fire in the lower floors on the east side of the building. The risers for the fuel distribution system were in one of the two utility shafts in the west end of the building. One exception was the American Express Corporation, which had a generator with a 275-gallon tank on the west end of the 8th floor. This tank was the sole supply for the American Express generator and was not connected to any other fuel oil source. The 275-gallon tank was filled by bringing containers of fuel oil to the tank and transferring the oil into the tank. Except for the part of the diesel oil distribution system serving the SSB generators, all of the generators were located at the west end, with relatively short horizontal distribution piping.

The SSB system involved three separate generator locations on the 5th floor: three generator sets in the southwest corner of the building, two in the northwest section, and four in the northeast section. The distribution pipe was double-wall welded black iron with leak detection between the pipes. The outer pipe was at least 4 inches in diameter and the inner pipe at least 2-1/2 inches. The pipe traversed most of the length of the 5th floor immediately north of a concrete masonry wall running most of the length of the floor in an east-west direction. At the east end of the 5th floor and to the south of the wall was a 1- to 2-story mechanical equipment room. Transfer Trusses 1 and 2 were located in this room. The east end of Truss 1 was supported by a truss element that ran perpendicular (i.e., north-south) to the main east-west portions of the truss. There was a set of double doors opening from the mechanical room to the area containing the four generator sets previously mentioned. The fuel oil distribution pipe ran above this door several feet to the north of the masonry wall. The type, quality, and hardware on the door set are unknown. The position of the door (i.e., open or closed) at the time of the incident is also unknown. Also, no information was available in regard to the size of the undercut on the door.

The fuel oil pumps were powered from the generator sets. Fuel oil would have been pumped from the tanks when the emergency power system sensed a power interruption. The pump then operated in response to the pressure difference between the supply and return, and the pump would circulate oil as long as such a difference existed. Upon sensing a power interruption, the system would automatically switch to emergency mode. This would have been done with a transfer switch that monitored the building power supply and transferred to the emergency power system if the power from the Con Ed source was interrupted. It was also possible for the transfer to be made manually. Relative to continuity of power to the building, Con Ed reported that "the feeders supplying power to WTC 7 were de-energized at 9:59 a.m." It is believed that the emergency generators came on line immediately. It is also believed that some of them may have stopped operating because of the contamination of the intake air flowing into the carburetors and radiators. Except for the SSB system, where it is understood that a UPS system provided backup power to the 75-gpm pump, the flow of oil would stop and, as soon as the day tanks were empty, the involved generator set would stop running.

The SSB generators did not use day tanks. Instead there was a pressurized loop system that served all nine generators. As long as the 75-gpm pump continued to operate, a break in the line could, under some conditions, have a full or partial break that would not cause the system to shut down and could discharge up to the 75-gpm capacity of this positive displacement pump. It is understood that the SSB pump was supplied power from both the SSB generators and from the UPS.

Engineers from the New York State Department of Environmental Conservation investigated oil contamination in the debris of WTC 7. Their principal interest was directed to the various oils involved in the Con Ed equipment. However, they reported the following findings on fuel oil: "In addition to Con Ed's oil, there was a maximum loss of 12,000 gallons of diesel from two underground storage tanks registered as 7WTC." To date, the NY State Environmental Protection Agency (EPA) and DEC have recovered approximately 20,000 gallons from the other two intact 11,600-gallon underground fuel oil storage tanks at WTC 7.

Based on the listings in Table 5.2, it is probable that the 20,000 gallons that were recovered were from the Silverstein Properties' emergency power system. The data obtained from Silverstein indicate that the pumping rate from their tanks was 4.4 gpm. If the Silverstein pump had started pumping at 10 a.m., when Con Ed shut down power to the building immediately following the collapse of WTC 2, and continued pumping until the collapse of WTC 7 at 5:20 p.m., less than 2,000 gallons would have been used. The residual 20,000 gallons found in the two 12,000-gallon tanks, therefore, can not be used as an indicator of whether or not the Silverstein generator sets were on line and running.

Similarly, the SSB pump, which had a pumping rate of 75 gpm, would have drained the two 6,000-gallon tanks serving that system in less than 3 hours. This could have accounted for the lost 12,000 gallons reported by EPA or the tanks could have been ruptured and the oil spilled into the debris pile. Again, this is not a valid indicator of whether or not the SSB generator sets came on line. The NY State EPA indicates that the SSB tanks will be pulled from the debris in the near future. This may or may not give some indication of the amount of oil still in the tanks when they were crushed. If there is evidence that the majority of diesel fuel was still in the tanks, it can be concluded that the SSB system did not discharge diesel oil as hypothesized in Section 5.6.1. Conversely, evidence that indicates that the tanks were low on oil at the time of rupture, and that they were full at the start of the September 11 incident, would lend support to the hypothesis that the SSB system was operating and pumping oil from these tanks.

Currently, there are no data available on the post-collapse condition of the OEM 6,000-gallon tank located between the 2nd and 3rd floors. The OEM system also included a 275-gallon day tank located on the 7th floor. The OEM system had a fuel supply system with the capability of transferring fuel from the Silverstein tanks to the 6,000-gallon OEM tank. The OEM generator sets were located in the southwest portion of the 7th floor. OEM also had an 11,000-gallon potable water tank on the south side of the 7th floor.

The Secret Service diesel distribution system, like the OEM system, was designed to refurbish its supply from the Silverstein tanks. This appears to have been pumped directly to a day tank having an estimated capacity of 50 to 100 gallons located near the northwest corner of the 9th floor. The generator set was also in the same location.

The 275-gallon tank associated with the American Express generator was located at the west end of the 8th floor. If full, the 275 gallons represent a potential of about 600 MegaJoules, which would be enough to cause a serious fire that could spread to other fuels, but not felt to be enough to threaten the stability of the building's structural elements.

5.5 Timeline of Events Affecting WTC 7 on September 11, 2001

The effects of the collapse of WTC 1 and WTC 2, the ensuing fires in WTC 7, and the collapse of WTC 7 are discussed below. Figure 5-12 shows the vantage points of the photographs taken illustrating these effects, as well as the extent of the debris generated by each of the collapses.

5.5.1 Collapse of WTC 2

At 9:59 a.m., WTC 2 (the south tower) collapsed. The approximate extent of its debris is shown in Figure 5-12(A). It appears that the collapse of WTC 2 did not significantly affect the roof, or the east, west, and north elevations of WTC 7. It is unknown if there was any damage to the south elevation after WTC 2 collapsed, but both the covered, tubular pedestrian bridge (see Figure 5-13) and the Plaza bridge were still standing after the collapse of WTC 2.

5.5.2 Collapse of WTC 1

At 10:29 a.m., WTC 1 (the north tower) collapsed, sending its debris into the streets below. The extent and severity of the resulting damage to WTC 7 are currently unknown. However, from photographic evidence and eyewitness accounts discussed below, it was assumed that the south side of the building was damaged to some degree and that fires in WTC 7 started at approximately this time.

Figure 5-14 is an aerial photograph that shows the debris clouds spreading around WTC 7 just after the collapse of WTC 1. Figure 5-15 is a photograph of WTC 1 debris between the west elevation of WTC 7 and the Verizon building. Figure 5-12(B) shows a plan-view diagram approximating the extent of this debris just after the collapse of WTC 1.

It does not appear that the collapse of WTC 1 affected the roof, or the east, west, and north elevations of WTC 7 in any significant way. However, there was damage to the southwest corner of WTC 7 at approximately floors 8 to 20, 24, 25, and 39 to 46, as shown in Figure 5-16, a photograph taken from West Street.

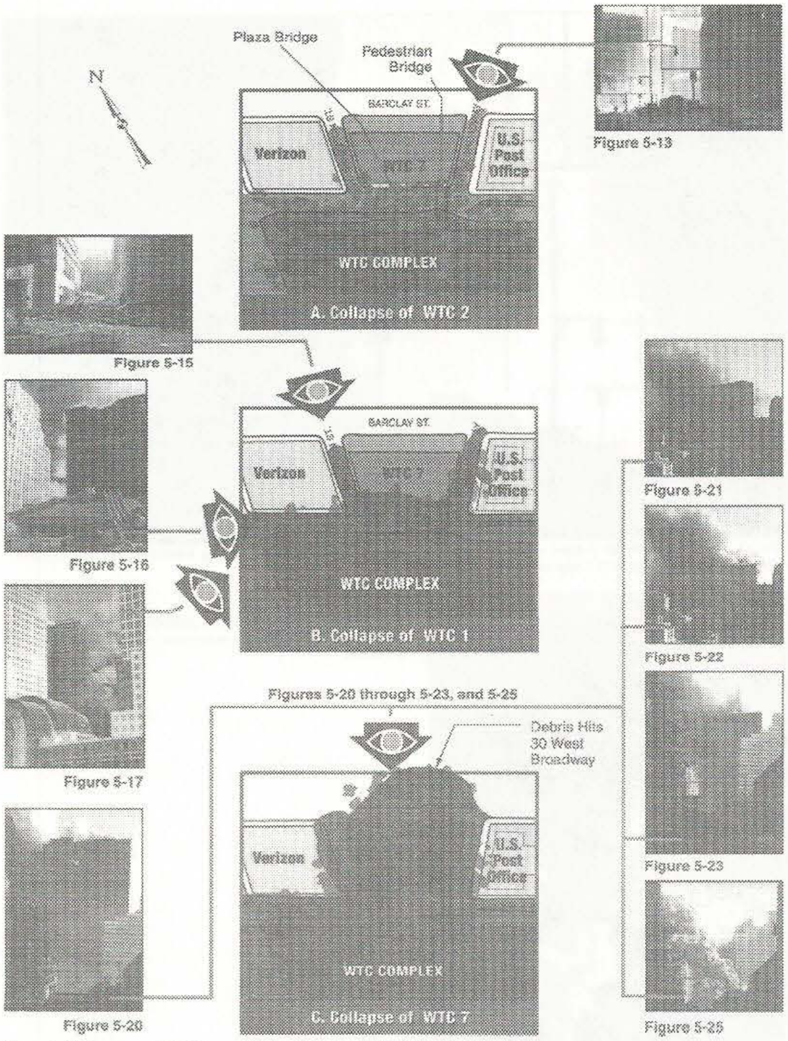

Plaza Bridge
Pedestrian Bridge
N
BARCLAY ST.
Verizon
WTC 7
U.S. Post Office
WTC COMPLEX
A. Collapse of WTC 2
Figure 5-13
Figure 5-15
Figure 5-16
Figure 5-17
BARCLAY ST.
Verizon
WTC 7
U.S. Post Office
WTC COMPLEX
B. Collapse of WTC 1
Figure 5-21
Figure 5-22
Figures 5-20 through 5-23, and 5-25
Debris Hits 30 West Broadway
Verizon
U.S. Post Office
WTC COMPLEX
C. Collapse of WTC 7
Figure 5-20
Figure 5-23
Figure 5-25

Figure 5-12 Sequence of debris generated by collapses of WTC 2, 1, and 7.

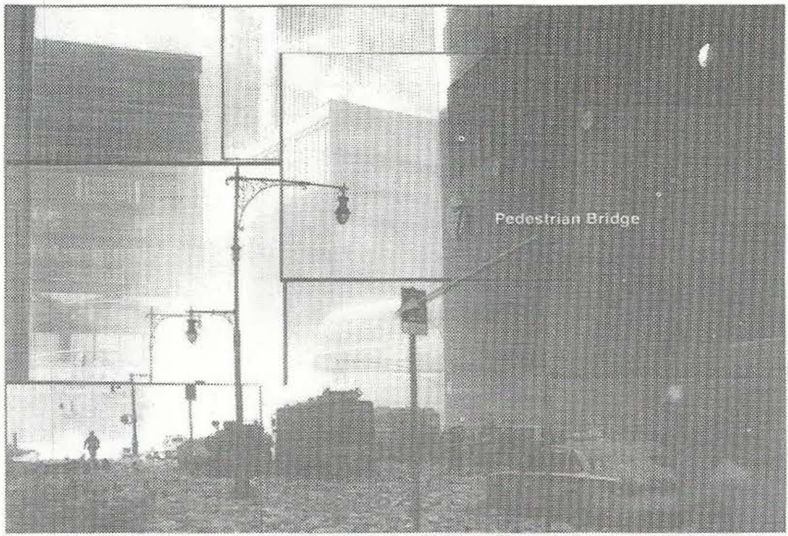


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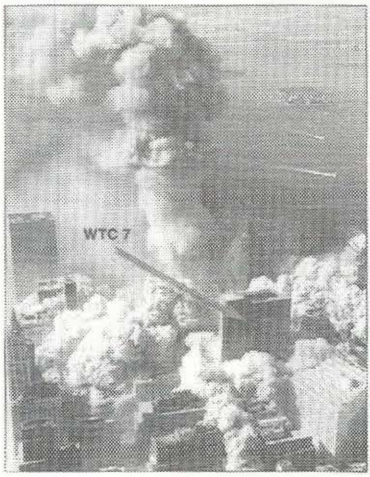
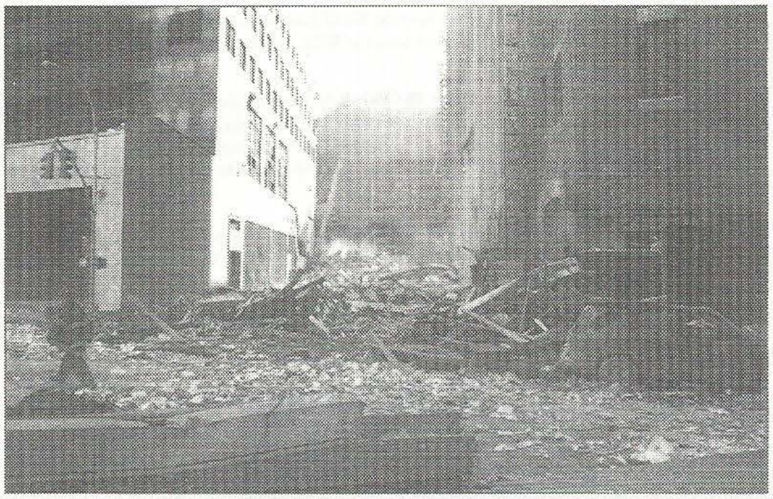
Figure 5-13 Pedestrian bridge (bottom center) still standing after WTC 2 has collapsed, sending substantial dust and debris onto the street, but before WTC 1 (top center) has collapsed.



OEM

Figure 5-14
View from the north of the WTC 1 collapse and spread of debris around WTC 7. Note the two mechanical penthouses of WTC 7 are intact.



GEORGE MILLER / NYC TA

Figure 5-15 Debris from the collapse of WTC 1 located between WTC 7 (left) and the Verizon building (right).

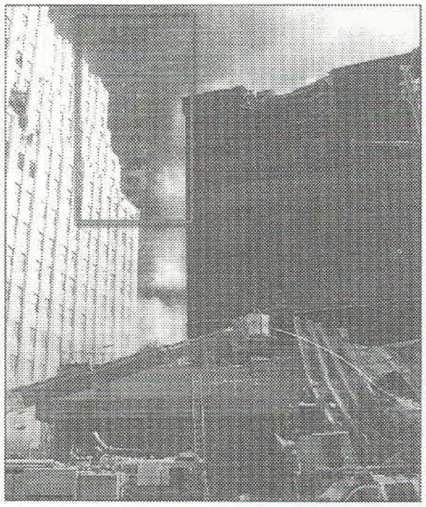


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Figure 5-16
Damage to southwest corner of WTC 7 (see box), looking from West Street.

Figure 5-17, a photograph taken across from the World Financial Center (WFC), shows the west elevation and indicates damage at the southwest corner of WTC 7 at the 24th, 25th, and 39th through 46th floors.

According to the account of a firefighter who walked the 9th floor along the south side following the collapse of WTC 1, the only damage to the 9th floor façade occurred at the southwest corner. According to firefighters' eyewitness accounts from outside of the building, approximately floors 8-18 were damaged to some degree. Other eyewitness accounts relate that there was additional damage to the south elevation.

5.5.3 Fires at WTC 7

Currently, there is limited information about the ignition and development of fires at WTC 7, as well as about the specific fuels that may have been involved during the course of the fire. It is likely that fires started as a result of debris from the collapse of WTC 1.

According to fire service personnel, fires were initially seen to be present on non-contiguous floors on the south side of WTC 7 at approximately floors 6, 7, 8, 10, 11, and 19. The presence of fire and smoke on

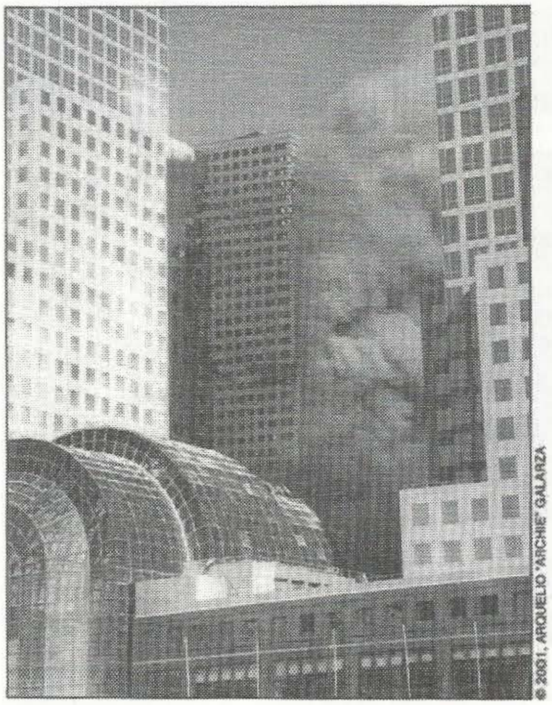

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Figure 5-17
Building damage to the southwest corner and smoke plume from south face of WTC 7, looking from the World Financial Plaza. Note damage to WFC 3 in the foreground.

lower floors is also confirmed by the early television news coverage of WTC 7, which indicated light-colored smoke rising from the lower floors of WTC 7.

Video footage indicated that the majority of the smoke appeared to be coming from the south side of the building at that time as opposed to the other sides of the building. This is corroborated by Figure 5-17, a photograph taken at 3:36 p.m. that shows the south face of WTC 7 covered with a thick cloud of smoke, and only small amounts of smoke emanating from the 27th and 28th floors of the west face of WTC 7.

News coverage after 1:30 p.m. showed light-colored smoke flowing out of openings on the upper floors of the south side of the building. Another photograph (Figure 5-18) of the skyline at 3:25 p.m., taken from the southwest, shows a large volume of dark smoke coming from all but the lowest levels of WTC 7, where white smoke is emanating. The mode of fire and smoke spread was unclear; however, it may have been propagated through interior shafts, between floors along the south façade that may have been damaged, or other internal openings, as well as the floor slab/exterior façade connections.

It appeared that water on site was limited due to a 20-inch broken water main in Vesey Street. Although WTC 7 was sprinklered, it did not appear that there would have been a sufficient quantity of water to control the growth and spread of the fires on multiple floors. In addition, the firefighters made the decision fairly early on not to attempt to fight the fires, due in part to the damage to WTC 7 from the collapsing towers. Hence, the fire progressed throughout the day fairly unimpeded by automatic or manual suppression activities.

A review of photos and videos indicates that there were limited fires on the north, east, and west faces of the building. One eyewitness who saw the building from a 30th floor apartment approximately 4 blocks

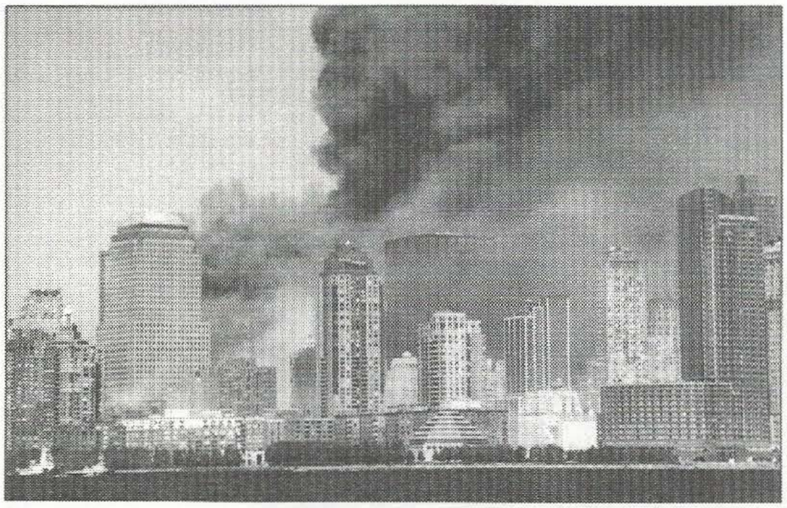

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Figure 5-18 WTC 7, with a large volume of dark smoke rising from it, just visible behind WFC 1 (left). A much smaller volume of white smoke is seen rising from the base of WTC 7. Note that the lower, lighter-colored smoke (to right) is thought to be from the two collapsed towers

away to the northwest noted that fires in the building were not visible from that perspective. On some of the lower floors, where the firefighters saw fires for extended periods of time from the south side, there appeared to be walls running in an east to west direction, at least on floors 5 and 6, that would have compartmentalized the north side from the south side. There were also air plenums along the east and west walls and partially along the north walls of these floors instead of windows that may have further limited fires from extending out of these floors and, therefore, were not visible from sides other than the south.

As the day progressed, fires were observed on the east face of the 11th, 12th, and 28th floors (see Figure 5-19). The Securities and Exchange Commission occupied floors 11 through 13. Prior to collapse, fire was seen to have broken out windows on at least the north and east faces of WTC 7 on some of the lower levels.

On the north face, photographs and videos show that the fires were located on approximately the 7th, 8th, 11th, 12th, and 13th floors. American Express Bank International occupied the 7th and 8th floors. The 7th floor also held the OEM generators and day tank. Photographs of the west face show fire and smoke on the 29th and 30th floors.

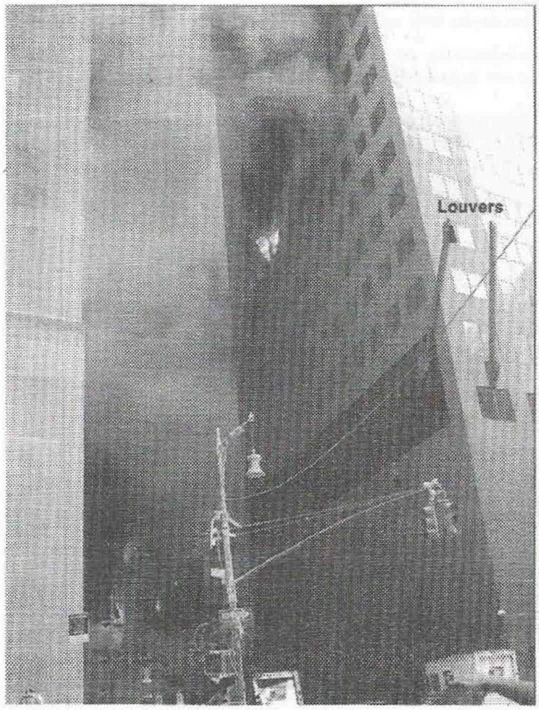

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Figure 5-19
Fires on the 11th and 12th floors of the east face of WTC 7.

It is important to note that floors 5 through 7 contained structural elements that were important to supporting the structure of the overall building. The 5th and 7th floors were diaphragm floors that contained transfer girders and trusses. These floors transferred loads from the upper floors to the structural members and foundation system that was built prior to the WTC 7 office tower. Fire damage in the 5th to 7th floors of the building could, therefore, have damaged essential structural elements.

With the limited information currently available, fire development in this building needs additional study. Fires were observed to be located on the lower levels for the majority of the time from the collapse of WTC 1 to the collapse of WTC 7. It appears that the sprinklers may not have been effective due to the limited water on site, and that the development of the fires was not significantly impeded by the firefighters because manual firefighting efforts were stopped fairly early in the day.

Available information indicates that fires spread horizontally and vertically throughout the building during the course of the day. The mode of spread was most likely either along the south façade that was damaged, or internally through shafts or the gap between the floor slab and the exterior wall. It is currently unclear what fuel may have been present to permit the fires to burn on these lower floors for approximately 7 hours. The change in the color and buoyancy of the smoke as the day progressed may indicate a change in the behavior of the fires. The darker color may be indicative of different fuels becoming involved, such as fuel oil, or the fire becoming ventilation limited. The increased buoyancy of the fires suggests that the heat release rate (or "fire size") may have also increased.

The mechanisms behind these apparent changes in behavior are currently unknown and therefore various scenarios need to be investigated further. These include gathering additional information regarding storage of materials on various levels, the quantity and combustibility of materials, and the presence of dense storage, including file rooms, tape vaults, etc. In addition, further analysis is needed on the specific locations of the fuel tanks, supply lines, fuel pumps, and generators to determine whether it may have been possible for a fuel line to be severed by the falling debris, allowing the pumps to run and pump fuel out of the broken pipes.

5.5.4 Sequence of WTC 7 Collapse

Approximately 7 hours after fires initiated in WTC 7, the building collapsed. The start of a timed collapse sequence was based on 17:20:33, the time registered by seismic recordings described in Table 1.1 (in Chapter 1). The time difference between each of the figures was approximated from time given on the videotape. Figures 5-20 to 5-25 illustrate the observed sequence of events related to the collapse.

~5:20:33 p.m. WTC 7 begins to collapse. Note the two mechanical penthouses at the roof on the east and west sides in Figure 5-20.

~5:21:03 p.m. Approximately 30 seconds later, Figure 5-21 shows the east mechanical penthouse disappearing into the building. It takes a few seconds for the east penthouse to "disappear" completely.

~5:21:08 p.m. Approximately 5 seconds later, the west mechanical penthouse disappears (Figure 5-22) or sinks into WTC 7.

~5:21:09 p.m. Approximately 1 or 2 seconds after the west penthouse sinks into WTC 7, the whole building starts to collapse. A north-south "kink" or fault line develops along the eastern side as the building begins to come down at what appears to be the location of the collapse initiation (see Figures 5-23 and 5-24).

~5:21:10 p.m. WTC 7 collapses completely after burning for approximately 7 hours (Figure 5-25). The collapse appeared to initiate at the lower floors, allowing the upper portion of the structure to fall.

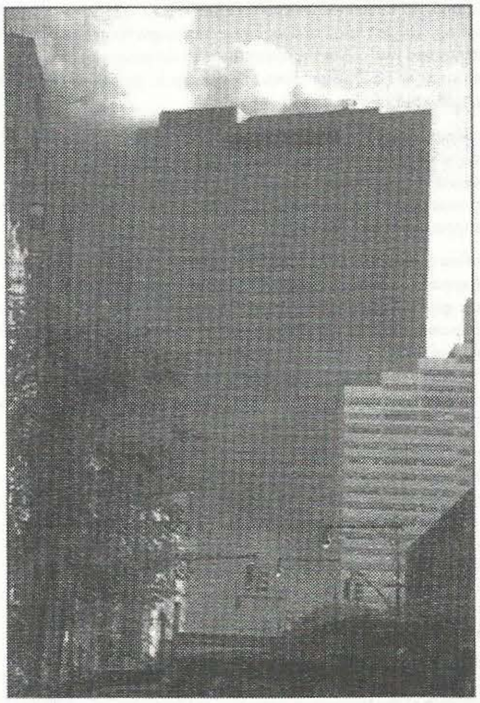

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Figure 5-20
View from the north of WTC 7 with both mechanical penthouses intact.

The debris generated by the collapse of WTC 7 spread mainly westward toward the Verizon building, and to the south. The debris significantly damaged 30 West Broadway to the north, but did not appear to have structurally damaged the Irving Trust building at 101 Barclay Street to the north or the Post Office at 90 Church Street to the east. The average debris field radius was approximately 70 feet. Figures 5-12(C) and 5-26 show an approximation of the extent of the debris after the collapse of WTC 7.

5.6 Potential Collapse Mechanism

5.6.1 Probable Collapse Initiation Events

WTC 7 collapsed approximately 7 hours after the collapse of WTC 1. Preliminary indications were that, due to lack of water, no manual firefighting actions were taken by FDNY.

Section 5.5.4 describes the sequence of the WTC 7 collapse. The described sequence is consistent with building collapse resulting from an initial (triggering) failure that occurred internally in the east portion of a lower floor in the building. There is no clear evidence of exactly where or on which floor the initiating failure occurred. Possibilities can be divided into three potential scenarios based on floor. In each case, the concern is

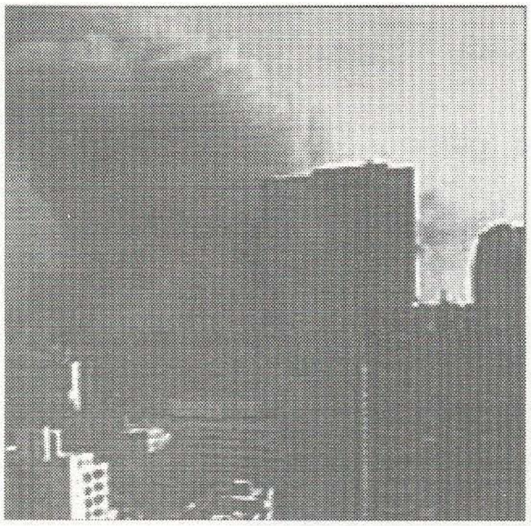

Figure 5-21
East mechanical penthouse collapsed. (From video.)

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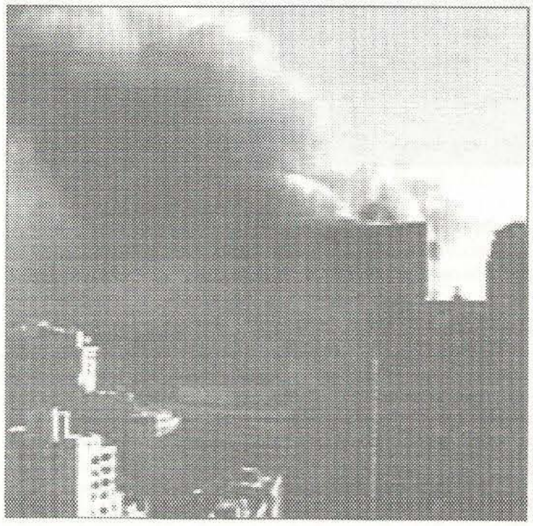

Figure 5-22
East and now west mechanical penthouses gone. (From video.)

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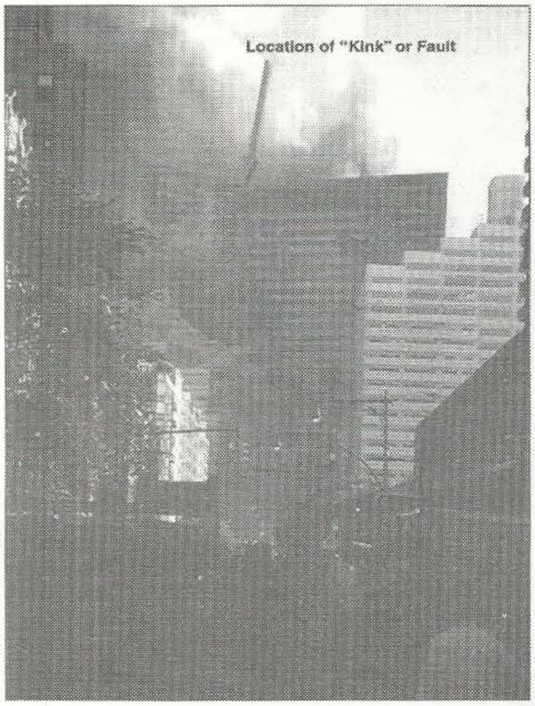

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Figure 5-23
View from the north of the "kink" or fault developing in WTC 7.

the failure of either a truss or one or more columns in the lower floors of the east portion of the building. Each of the scenarios is a hypothesis based on the facts known and the unknown conditions that would be required for the hypothesis to be valid. The cases are presented not as conclusions, but as a basis for further investigation.

4th Floor Scenarios. The bottom cords of the transfer trusses were part of the support of the 5th floor slab and, as such, were located below the slab and above the ceiling of the 4th floor in a position exposed to fire from below. The bottom cord members were massive members weighing slightly over 1,000 pounds per foot. Such members are slow to heat up in a fire. It was reported that these bottom cords were fireproofed. The space below was the cafeteria dining room. The best information available indicates that the dining room was furnished with tables and chairs. The intensity and duration of a fire involving these furnishings would not be expected to sufficiently weaken either the trusses or the columns supporting the trusses. Member collapse as a result of a fire on the 4th floor would require either that there was significant additional fuel or that the fireproofing on the trusses or columns was defective. Fuel oil leakage from the 5th floor is also a possibility; however, no evidence of leakage paths in the east end of the second floor was reported.

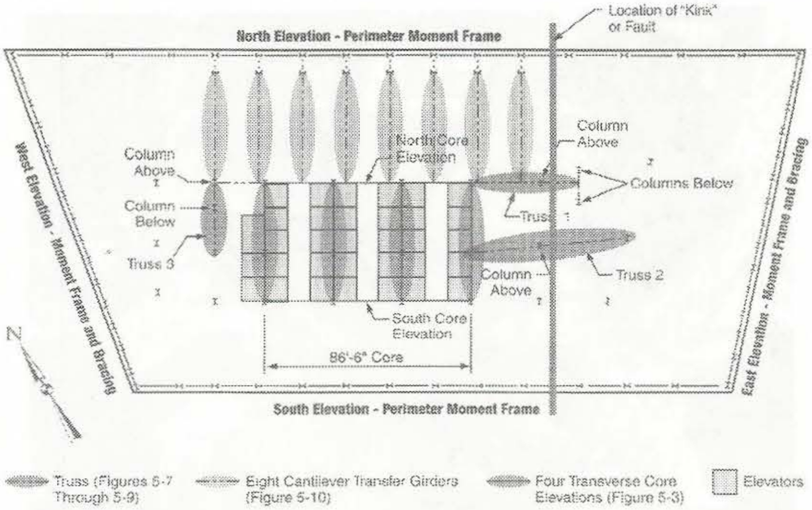
Location of "Kink" or Fault
North Elevation - Perimeter Moment Frame
West Elevation - Moment Frame and Bracing
East Elevation - Moment Frame and Bracing
South Elevation - Perimeter Moment Frame
Column Above
Column Below
Truss 3
North Core Elevation
Column Above
Columns Below
Truss 1
Column Above
Truss 2
South Core Elevation
86'-6" Core
N
Truss (Figures 5-7 Through 5-9)
Eight Cantilever Transfer Girders (Figure 5-10)
Four Transverse Core Elevations (Figure 5-3)
Elevators

Figure 5-24 Areas of potential transfer truss failure.

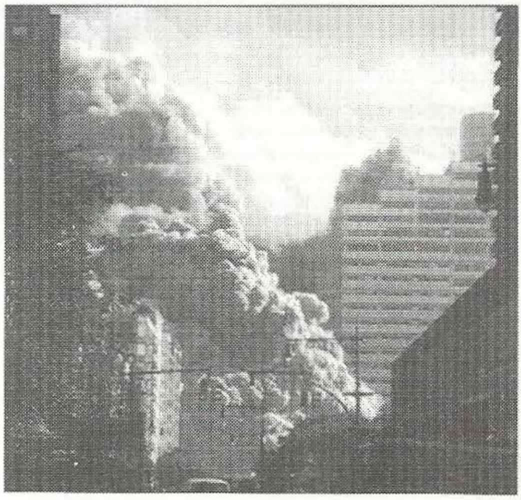

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Figure 5-25 Debris cloud from collapse of WTC 7.

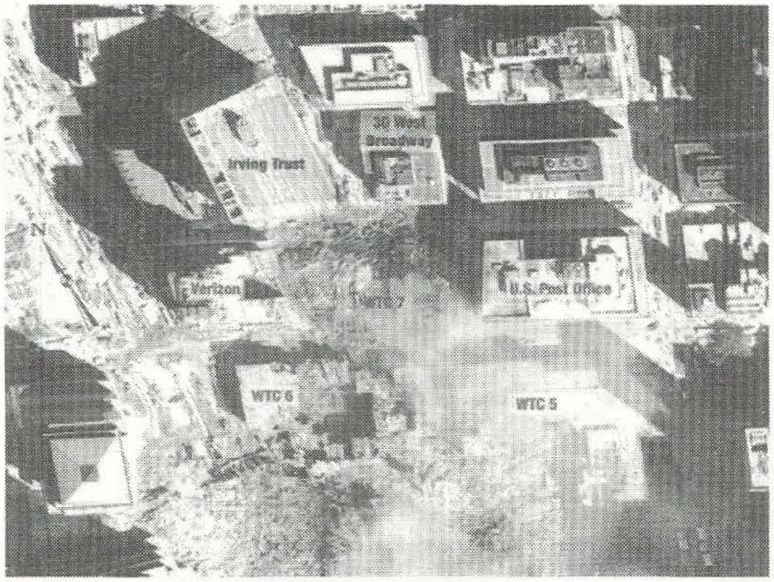

Figure 5-26 Debris generated after collapse of WTC 7.

5th Floor Scenarios. From a structural standpoint, the most likely event would have been the collapse of Truss 1 and/or Truss 2 located in the east end of the 5th and 6th floors. These floors are believed to have contained little if any fuel other than the diesel fuel for the emergency generators, making diesel oil a potential source of fire. As noted in Section 5.4, the fuel distribution system for the emergency generators pumped oil from tanks on the lower floors to the generators through a pipe distribution system. The SSB fuel oil system was a more likely source of fire around the transfer trusses. The SSB pump is reported as a positive displacement pump having a capacity of 75 gpm at 50 psi. Fuel oil was distributed through the 5th floor in a double-wall iron pipe. A portion of the piping ran in close proximity to Truss 1. However, there is no physical, photographic, or other evidence to substantiate or refute the discharge of fuel oil from the piping system.

The following is, therefore, a hypothesis based on potential rather than demonstrated fact. Assume that the distribution piping was severed and discharged up to 75 gpm onto the 5th floor in the vicinity of Truss 1. Seventy-five gpm of diesel fuel have the potential of approximately 160 megawatts (MW) of energy. If this burning diesel fuel formed pools around Truss 1, it could have subjected members of that truss to temperatures significantly in excess of those experienced in standard fire resistance test furnaces (see Appendix A). If the supply tanks were full at the start of the discharge, there was enough fuel to sustain this flow for approximately 3 hours. If the assumed pipe rupture were incomplete and the flow less, the potential burning rate of the discharged oil would be less, but the duration would be longer. At even a 30-gpm flow rate (about 60 MW potential), the exposed members in the truss could still be subjected to high temperatures that would progressively weaken the steel. For the above reasons, it is felt that burning of discharged diesel fuel oil in a pool encompassing Truss 1 and/or Truss 2 needs to be further evaluated as a possible cause of the building collapse.

In evaluating the potential that a fire fed by fuel oil caused the collapse, it is necessary to determine whether the following events occurred:

1. The SSB generators called for fuel. This would occur once the generators came on line.
2. The pumps came on, sending fuel through the distribution piping.
3. There was a breach in the fuel distribution piping and fuel oil was discharged from the distribution system.

   Although there is no physical evidence available, this hypothesis assumes that it is possible that both the inner and outer pipes were severed, presumably by debris from the collapse of WTC 1. Depending on ventilation sources for air, this is sufficient to flashover the space along the north wall of this floor. The temperature of the fire gases would be governed to a large extent by the availability of air for combustion. The hot gases generated would be blocked from impacting Trusses 1 and 2 by the masonry wall separating the generation area from the mechanical equipment room, assuming that this wall was still intact after collapse of the tower and there were no other significant penetrations of walls.
4. The discharged fuel must be ignited.

   For diesel oil to be ignited, there must be both an ignition source and the oil must be raised to its flash point temperature of about 60 °C (140 °F). Because there were fires on other floors of WTC 7, an assumption of ignition at this level in the building is reasonable, but without proof.
5. There is sufficient air for combustion of the discharged fuel oil.

   The air required for combustion of 75-gpm (160 MW potential) diesel fuel is approximately 100,000 cubic feet per minute (cfm). If less air is available for combustion, the burning rate will decrease proportionally. As the engine generator sets come on line, automatic louvers open and 80,000 cfm are provided for each of the nine SSB engines. A portion is used as combustion air for the drive engines; the rest is for cooling, but could supply air to an accidental fire. Given open louvers and other sources for entry of air, it is, therefore, probable that a fuel oil spill fire would have found sufficient air for combustion.
6. The hot fire gases reach and heat the critical member(s).

   For this to happen, the fire must have propagated either fuel or hot gases to the members in the truss in the mechanical equipment room. If the double door to the mechanical equipment room was either open or fell from its frame at some point, or if the door was undercut, the spilled fuel oil might have flowed into the mechanical equipment room, enveloping truss members in the main (hottest) portion of the flame. Such a situation could produce an exposure possibly exceeding that in the standard furnace test producing localized heat fluxes approaching the 200 kW/m^2 used by Underwriters Laboratories to simulate a hydrocarbon pool fire, with exposure temperatures in the range of 1,200 °C (2,200 °F). If such intense exposure existed, the steel would be weakened more rapidly than normally expected. If the door was of superior construction (as with a fire door), it is unlikely that the fire would have reached the trusses in the mechanical equipment room until such time that the door failed.

A further hypothesis that would help explain the long time lapse between the collapse of WTC 1 and the collapse of WTC 7 would be that the masonry wall and door resisted the fire for a number of hours, but eventually failed. The new opening then allowed the fire (still supplied with a continuous discharge of fuel oil) to flow into the mechanical equipment room, envelope elements of the fireproofed trusses, and eventually cause a buckling collapse of one or both of them. For the fire to last long enough for this to occur, the flow rate would have to be around 30 gpm. At a rate of 30 gpm, the fuel would last for about 7 hours and would produce a fire of about 60 MW. The possibility that such a scenario could occur would be dependent on the specific construction details of the wall, the door, and the fireproofing on the truss.

Another hypothesis that has been advanced is that the pipe was penetrated by debris at a point near the southwest corner where there was more damage caused by debris from the collapse of the towers. This would have resulted in fuel oil spilling onto the 5th floor, but not being immediately ignited. However, a major portion of the 12,000 gallons in the SSB tanks would pump out onto the 5th floor, forming a large pool. At some point, this would have ignited and produced the required fire. This hypothesis has the advantage of assuming a pipe break in the area most severely impacted by the tower debris and accounts for the long delay from the initial incident to the collapse of WTC 7. The principal challenge is that such a fire would have more severely exposed Truss 3. If Truss 3 had been the point of collapse initiation, it is not expected that the first apparent sign of collapse would be the subsidence of the east penthouse.

Evaluation of fires on the 3rd to 6th floors is complicated by the fact that these floors were windowless with louvers, generally in a plenum space separating any direct line of sight between the open floor space and the louvers. None of the photographic records found so far show fires on these floors.

Further investigation is required to determine whether the preceding scenarios did or could have actually occurred.

Other Involved Floors Scenarios. Fire was known to have occurred on other floors. If a fire on one of these floors involved a large concentration of combustible material encasing several columns in the east portion of the floor, it might have been of sufficient severity to cause the structural members to weaken. Such fuel concentrations might have been computer media vaults, archives and records storage, stock or storage rooms, or other collections. It is possible that the failure of at least two or possibly more columns on the same floor would have been enough to cause collapse.

5.6.2 Probable Collapse Sequence

The collapse of WTC 7 appears to have initiated on the east side of the building on the interior, as indicated by the disappearance of the east penthouse into the building. This was followed by the disappearance of the west penthouse, and the development of a fault or "kink" on the east half of WTC 7 (see Figures 5-23 and 5-24). The collapse then began at the lower floor levels, and the building completely collapsed to the ground. From this sequence, it appears that the collapse initiated at the lower levels on the inside and progressed up, as seen by the extension of the fault from the lower levels to the top.

During the course of the day, fires may have exposed various structural elements to high temperatures for a sufficient period of time to reduce their strength to the point of causing collapse. The structural elements most likely to have initiated the observed collapse are the transfer trusses between floors 5 to 7, located on lower floors under the east mechanical penthouse close to the fault/kink location.

If the collapse initiated at these transfer trusses, this would explain why the building imploded, producing a limited debris field as the exterior walls were pulled downward. The collapse may have then spread to the west. The building at this point may have had extensive interior structural failures that then led to the collapse of the overall building. The cantilever transfer girders along the north elevation, the strong diaphragms at the 5th and 7th floors, and the seat connections between the beams and columns at the building perimeter may have become overloaded after the collapse of the transfer trusses and caused the interior collapse to propagate to the whole floor and to the exterior frame. The structural system between floors 5 and 7 appears to be critical to the structural performance of the entire building.

An alternative scenario was considered in which the collapse started at horizontal or inclined members. The horizontal members include truss tension ties and the transfer girder of the T-1 truss at the east side of the 5th floor. Inclined members spanned between the 5th and 7th floors and were located in a two-story open mechanical room. The horizontal haunched back span of the eastern cantilever transfer girders, located roughly along the kink, rested on a horizontal girder at the 7th floor supported by the T-1 transfer truss. Even if the cantilever transfer girder had initiated the collapse sequence, the back span failure would most likely have not caused the observed submergence of the east mechanical penthouse.

The collapse of WTC 7 was different from that of WTC 1 and WTC 2, which showered debris in a wide radius as their frames essentially "peeled" outward. The collapse of WTC 7 had a small debris field as the façade was pulled downward, suggesting an internal failure and implosion.

To confirm proposed failure mechanisms, structural analysis and fire modeling of fuels and anticipated temperatures and durations will need to be performed. Further study of the interaction of the fire and steel, particularly on the lower levels (i.e., 1st–12th floors) should be undertaken to determine specific fuel loads, location, potential for impact from falling debris, etc. Further research is needed into location of storage and file room combustible materials and fuel lines, and the probability of pumps feeding fuel to severed lines.

5.7 Observations and Findings

This office building was built over an electrical substation and a power plant, comparable in size to that operated by a small commercial utility. It also stored a significant amount of diesel oil and had a structural system with numerous horizontal transfers for gravity and lateral loads.

The loss of the east penthouse on the videotape suggests that the collapse event was initiated by the loss of structural integrity in one of the transfer systems. Loss of structural integrity was likely a result of weakening caused by fires on the 5th to 7th floors. The specifics of the fires in WTC 7 and how they caused the building to collapse remain unknown at this time. Although the total diesel fuel on the premises contained massive potential energy, the best hypothesis has only a low probability of occurrence. Further research, investigation, and analyses are needed to resolve this issue.

The collapse of WTC 7 was different from that of WTC 1 and WTC 2. The towers showered debris in a wide radius as their external frames essentially "peeled" outward and fell from the top to the bottom. In contrast, the collapse of WTC 7 had a relatively small debris field because the façade came straight down, suggesting an internal collapse. Review of video footage indicates that the collapse began at the lower floors on the east side. Studies of WTC 7 indicate that the collapse began in the lower stories, either through failure of major load transfer members located above an electrical substation structure or in columns in the stories above the transfer structure. Loss of strength due to the transfer trusses could explain why the building imploded, with collapse initiating at an interior location. The collapse may have then spread to the west, causing interior members to continue collapsing. The building at this point may have had extensive interior structural failures that then led to the collapse of the overall building, including the cantilever transfer girders along the north elevation, the strong diaphragms at the 5th and 7th floors, and the seat connections between the interior beams and columns at the building perimeter.

5.8 Recommendations

Certain issues should be explored before final conclusions are reached and additional studies of the performance of WTC 7, and related building performance issues should be conducted. These include the following:

- Additional data should be collected to confirm the extent of the damage to the south face of the building caused by falling debris.
- Determination of the specific fuel loads, especially at the lower levels, is important to identify possible fuel supplied to sustain the fires for a substantial duration. Areas of interest include storage rooms, file rooms, spaces with high-density combustible materials, and locations of fuel lines. The control and operation of the emergency power system, including generators and storage tanks, needs to be thoroughly understood. Specifically, the ability of the diesel fuel pumps to continue to operate and send fuel to the upper floors after a fuel line is severed should be confirmed.
- Modeling and analysis of the interaction between the fires and structural members are important. Specifically, the anticipated temperatures and duration of the fires and the effects of the fires on the structure need to be examined, with an emphasis on the behavior of transfer systems and their connections.
- Suggested mechanisms for a progressive collapse should be studied and confirmed. How the collapse of an unknown number of gravity columns brought down the whole building must be explained.
- The role of the axial capacity between the beam-column connection and the relatively strong structural diaphragms may have had in the progressive collapse should be explained.
- The level of fire resistance and the ratio of capacity-to-demand required for structural members and connections deemed to be critical to the performance of the building should be studied. The collapse of some structural members and connections may be more detrimental to the overall performance of the building than other structural members. The adequacy of current design provisions for members whose failure could result in large-scale collapse should also be studied.

5.9 References

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6 Bankers Trust Building

6.1 Introduction

The Bankers Trust building at 130 Liberty Street, also referred to as the Deutsche Bank building, withstood the impact of one or more pieces of column-tree debris raining down from the collapsing south tower (WTC 2). Although the debris sliced through the exterior façade, fracturing spandrel beam connections and exterior columns for a height of approximately 15 stories, the building sustained only localized damage in the immediate path of the debris from WTC 2 (hereafter referred to as the impact debris) (Figures 6-1 and 6-2). There were no fires in this building. The ability of this building to sustain significant structural damage yet arrest the progression of collapse is worthy of thorough study. Unlike WTC 1, 2, and 7, which collapsed completely, the Bankers Trust building provided an opportunity to analyze a structure that suffered a moderate level of damage, to explain the structural behavior, and to verify the analytical methods used. The following sections describe the building structure, the extent of damage, and the computational methods that were used to analyze the structure.

6.2 Building Description

The Bankers Trust building is a steel-frame commercial office structure, designed and constructed circa 1971. Bankers Trust was designed by Shreve, Lamb & Harmon Associates P. C. Architects; Peterson and Brickbauer Associated Architects; the Office of James Rudderman Structural Engineers, and Jaros Baum and Bolles Mechanical and Electrical Engineers. The building measures 560 feet in height with 40 stories above grade and 2 below. It is located directly across Liberty Street from the former site of WTC 2, about 600 feet due south of the southeast corner of WTC 2. The floor numbering used in the building elevator system and referred to in this report omits the 13th floor and includes a mezzanine between the 5th and 6th floors.

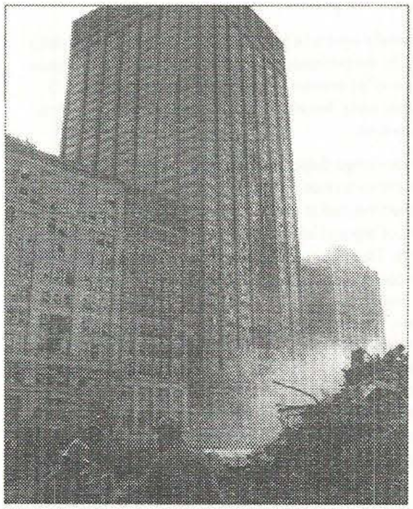


Figure 6-1
North face of Bankers Trust building with impact damage between floors 8 and 23.

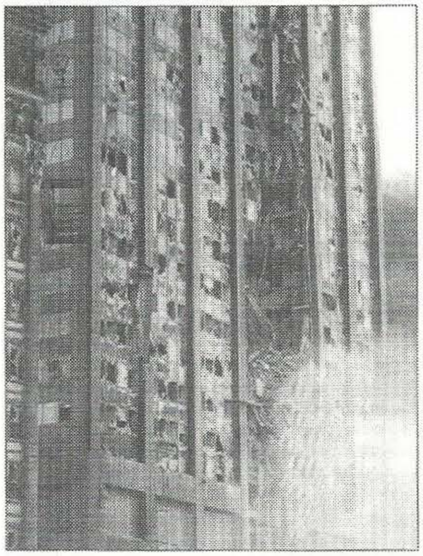
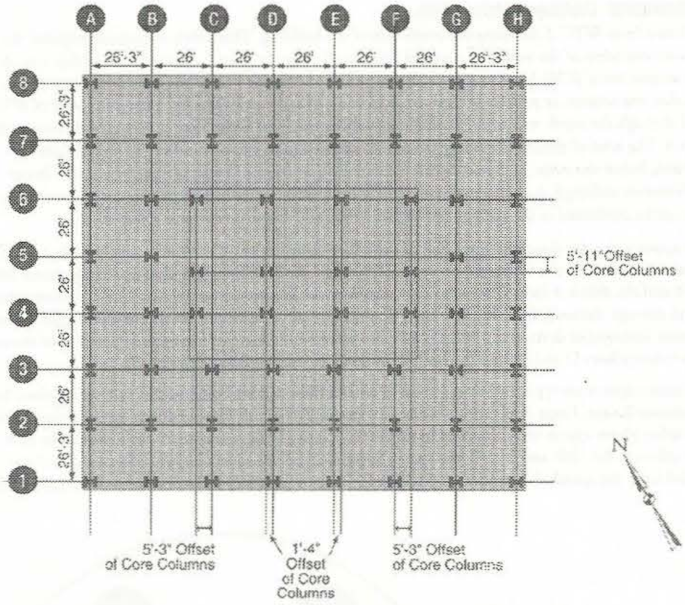


Figure 6-2
Closeup of area of partial collapse. Note debris accumulated at the bottom of the damage area, resting on the 8th floor. Area of initial impact is not shown in this photo.

Above the second floor level, the building is essentially square in plan shape, with overall dimensions (centerline of exterior column lines) of 183 feet square. At the perimeter of the building, layout of columns in both the north-south and east-west directions consists of an exterior bay on each end that is 26 feet 3 inches wide and five interior bays that are 26 feet 0 inches wide. Interior column spaces vary slightly from this to accommodate the central elevator core (see Figure 6-3).

Girders and spandrel beams are typically deep wide-flange shapes, including W24, W27, W30, and W36 sections, but also including occasional built-up sections termed "wind girders." Girders and spandrel beams are moment-connected to columns at each intersection and at both axes of the columns. The girders' moment connections to column flanges were composed of top and bottom plates filler-welded to the beam flanges and full-penetration welded to the column flange. These connections were designed for wind moment only, not the flexural capacity of the members, and are considered to be fully restrained, partial-strength connections. Lateral drift (stiffness) due to wind loads usually controls the design for moment frames. The beam web was connected to the column via a shear plate, fillet-welded to the column and bolted to the beam web. Girders that were connected to the column web utilized top plates fillet-welded to the beam top flange and full-penetration weld to the column web: there was no connection to the inside face of the column flanges. The bottom flange of the girder was connected to an extended stiffened seat that had its seat plate full-penetration-welded to the column web. The beam web had no connection to the column because the seated connection provided the necessary shear transfer. Girder-to-column shear connections utilize A325 high-strength bolts. Steel grade is ASTM A572 grade 50 except for the wind girders, which are A36. The columns are generally A36, except that some A588 steel is used at lower-level columns.


A
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6
5
4
3
2
1
26'-3"
26'
26'
26'
26'
26'
26'-3"
5'-11"Offset of Core Columns
5'-3" Offset of Core Columns
1'-4" Offset of Core Columns
5'-3" Offset of Core Columns
N

Figure 6-3 Floor plan above the 2nd level (ground floor extension not shown).

Floor beams are typically non-composite and consist of rolled W14, W16, and W18 shapes spanning north to south between girders, typically spaced at 8 feet 8 inches. The floor beams are fastened to the girders via shear connections and typically utilize a partial end plate welded to the floor beam and bolted to the girder with A307 bearing bolts. The floor itself typically consists of 1-1/2- inch metal deck supporting a 2-1/2-inch lightweight concrete slab. Floor beams are typically depressed 2 1/2 inches relative to the girders. Typical floor height (above the 5th floor) is 12 feet 2 inches. All beam-to-beam connection bolts appear to be A307. To accommodate this limited height, limited depth members with Grade 50 (50 ksi yield strength) steel were used.

A mechanical floor is present at the 5th level, and this story is taller, at 20 feet 8 inches. The stories below the 5th level are also taller than typical, with heights varying from 16 feet to 20 feet. To laterally stiffen the frame in these tall stories, a system of diagonal bracing is provided at the elevator core.

At the first story, the building extended outward to the north, with a large canopy structure. The canopy structure extended several column lines to the north of the main building line. A full basement underlies the entire structure.

6.3 Structural Damage Description

Debris from WTC 2 fell along the north side of the building. This debris completely crushed the single-story extension of the building, north of line 8, and collapsed it into the basement in this area. A column section from WTC 2 was embedded in the north edge of the floor slab of the 29th floor. It also appears that one section, or perhaps several sections, of exterior column trees from the south wall of WTC 2 plunged through the north wall of the building just above the 23rd floor. This impact area is illustrated in Figure 6-4. The zone of structural damage remained confined to one structural bay for several floors immediately below the point of impact before spreading to two and sometimes three bays in the floors below. However, although the pattern of damage was influenced by the structural response, most of the damage can be attributed to the path of the impact debris and not to progressive collapse.

It appears that the direction of motion of the falling debris from WTC 2 was steeply angled down and to the east-southeast. As the falling debris smashed through the 23rd floor spandrel between column lines C and D, it and the debris it created at each floor continued to dive deeper into the building, causing more structural damage. Between the 19th and 22nd floors, the floor areas between column lines 7 and 8, and C and D were damaged or destroyed (Figure 6-5). The damage zone increased to include portions of the area between column lines D and E from the 18th floor down to the 9th floor (Figure 6-5).

Column splices are typically located at every second floor and are composed of thin splice plates bolted to the column flanges. Large axial tension loads were probably not a design condition for the column splices, and the splice plates appear to be minimal in thickness, offering little resistance to separation. The D-8 column splices at the 18th and 16th floors appear to have been overloaded, leaving a section of column suspended from the spandrels at floors 16 through 18. The column below this level and down to the 8th

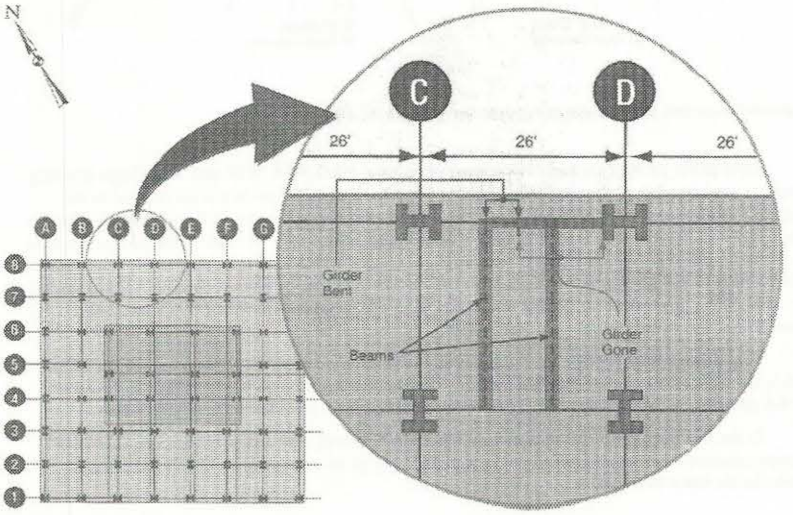
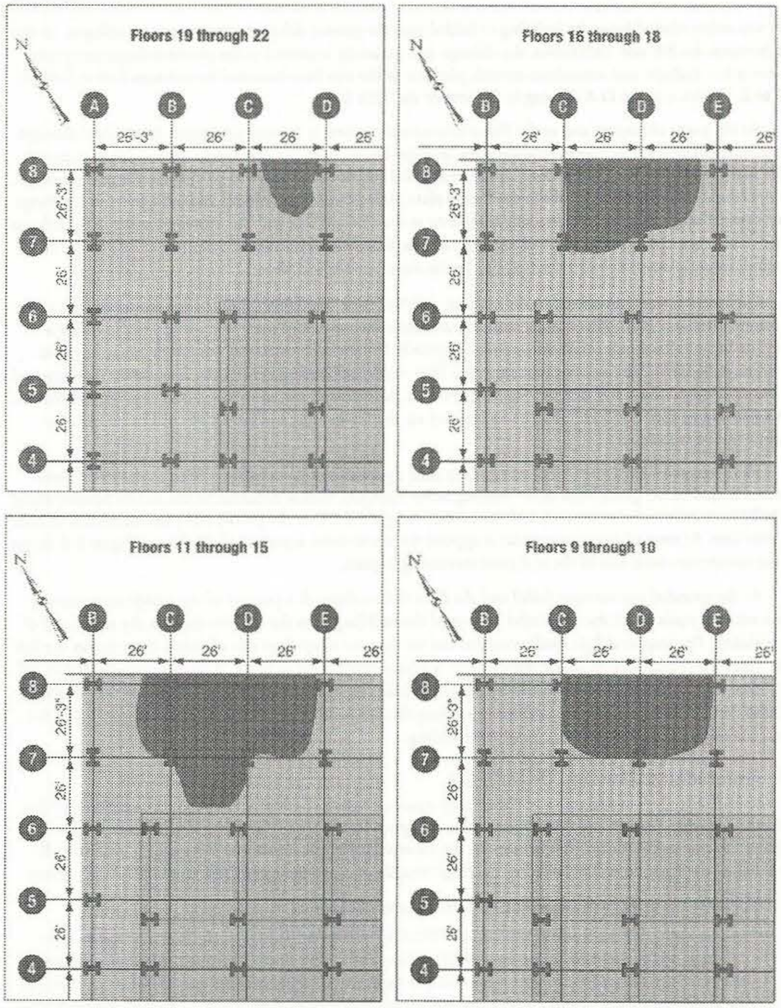


Figure 6-4 Area of initial impact of debris at the 23rd floor.



Floors 19 through 22

Floors 16 through 18

Floors 11 through 15

Floors 9 through 10

Figure 6-5 Approximate zones of damage – 19th through 22nd floors, 16th through 18th floors, 11th through 15th floors, and 9th through 10th floors.

floor was either ejected from the building or folded into the general debris during the partial collapse. In the area between the 8th and 16th floors, the damage area generally increased as the partial collapse progressed downward to include, and sometimes exceed, portions of the two bays bounded by columns C-8 to E-8 and C-7 to E-7, with column D-8 missing in the area of the 12th floor.

At the point of impact and at the floors immediately below, it appears the impact debris sliced through the spandrels. However, at lower elevations, the spandrel beams were not fractured and separation occurred at the spandrel-to-column connections. In the typical failure mode of the girder-to-column-flange connection, the weld and heat-affected zone of the top flange plate pulled out of the column and left a crater in the flange. The bottom flange plate was overloaded in bending at the column face without creating a crater in the column flange. The beam shear connection was typically left in place. The shear failure occurred mostly in the beam web and, in some cases, through the bolt line in the shear connection plate.

Girders that were connected to the column web had their top flange plate overloaded in tension at the weld zone interface. Normally, a crater was created where the top flange plate was welded to the column web. The bottom flange sat on a stiffened seat. Typically, the seated connection was left in place; however, the beam pulled off of the seat, separating at the fillet welds and leaving behind the fillet welds that attached the beam flange to the seat top plate. Figure 6-6 shows the stiffened seat at the weak axis side of the column. Figure 6-7 shows that the shear connection remains on the flange side, but only a piece of beam remains hanging on the web side.

Floor-beam-to-girder connections typically used a partial-depth end plate welded to the floor beam web and bolted to the girder with A307 bearing bolts. Typically, failure occurred in one of two modes, either the bolts were overloaded in tension and the connection pulled off, or the partial end plate sheared at or near the weld line. At most of the connections, it appears there was some amount of bolt failure. Figure 6-8 shows a shear connection with half of the end plate remaining in place.

As the spandrel connections failed and the floor slabs collapsed, a portion of the rubble accumulated into a two-story pile while the remainder fell out of the building onto the low-rise roof on the north side of the building. The impact debris finally came to rest on the two-story-deep pile of debris that was on the 8th floor. Figures 6-9 and 6-10 illustrate the damage. A major component of WTC 2, approximately 40 feet tall by 30 feet wide, remained lodged in the debris pile and was clearly visible as it hung from the face of the building. Yet despite this weight, the floor supporting the debris deflected a maximum of 6 inches. Figure 6-11 shows the extent of debris in the lobby of the building.

6.4 Architectural Damage Description

In addition to the destruction of the canopy structure north of column line 8, and the collapse of the floor areas between the 8th and 23rd floors, there was general damage to the entire north façade of the building. Nearly every window was broken on the western half of the north face, between column lines B and E below the 23rd floor. This window breakage would appear to be attributable to the following causes:

- Localized damage in the areas impacted by column trees falling from WTC 2.
- Smaller debris blown from WTC 1 and WTC 2. In particular, several small chunks of lightweight concrete, which appeared to be from WTC 2 floor slabs, were thrown through the north windows of the building. These debris items ranged in size from small fragments that caused bullet-size holes in the windows to large chunks with a maximum dimension of approximately 12 inches. Many of these chunks landed as far as 15 feet from the exterior building line and appeared to be traveling almost horizontally when they penetrated the building façade.

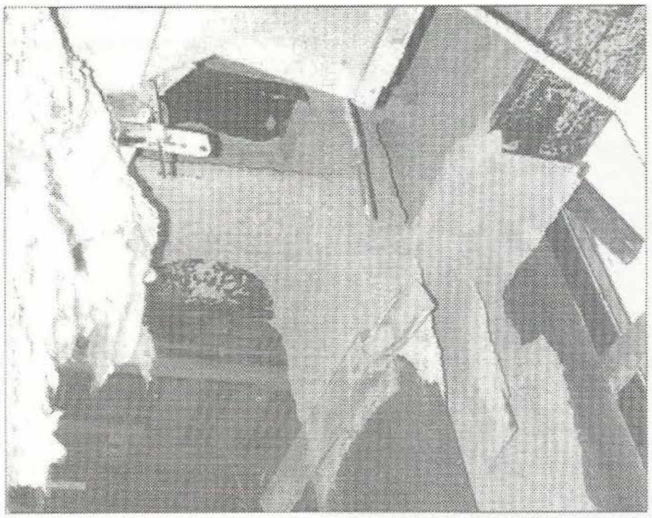


Figure 6-6 Moment-connected beams to columns.

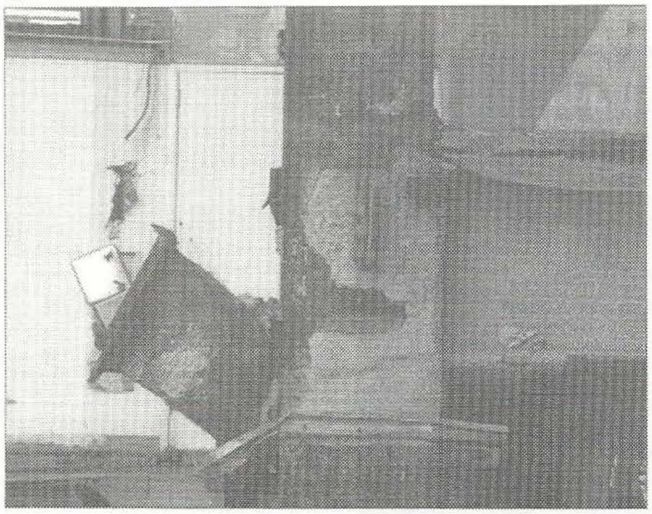


Figure 6-7 Column with the remains of two moment connections.

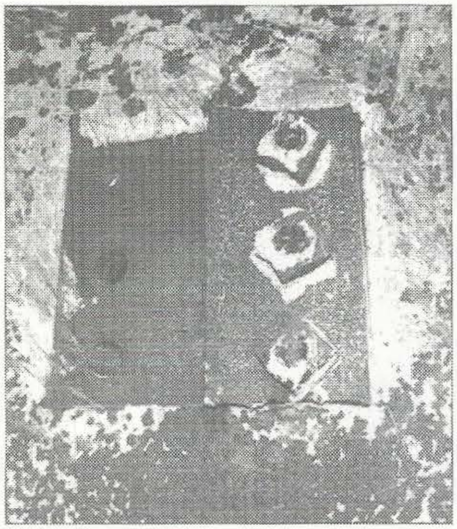


Figure 6-8
Failed shear connection of beam web to column web.

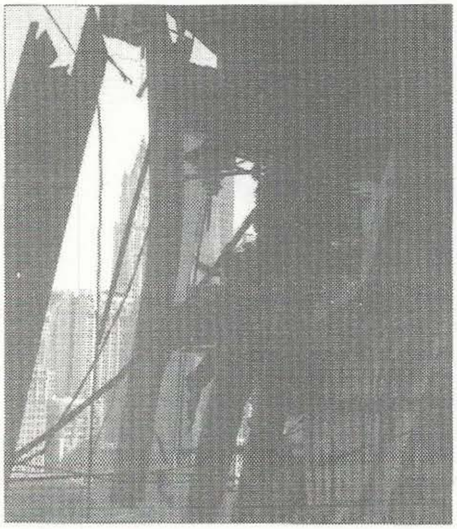


Figure 6-9
Suspended column D-8 at the 15th floor. Note separation at column splices.

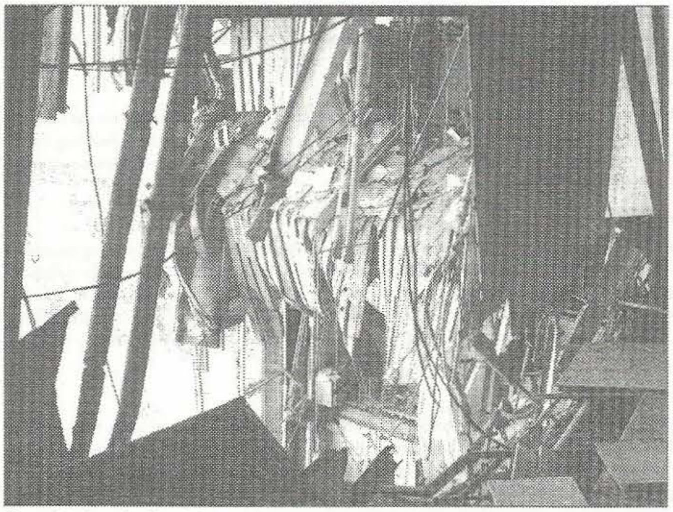


Figure 6-10 Area of collapsed floor slab in bays between C-8, E-8, C-7, and E-7, from the 15th floor.

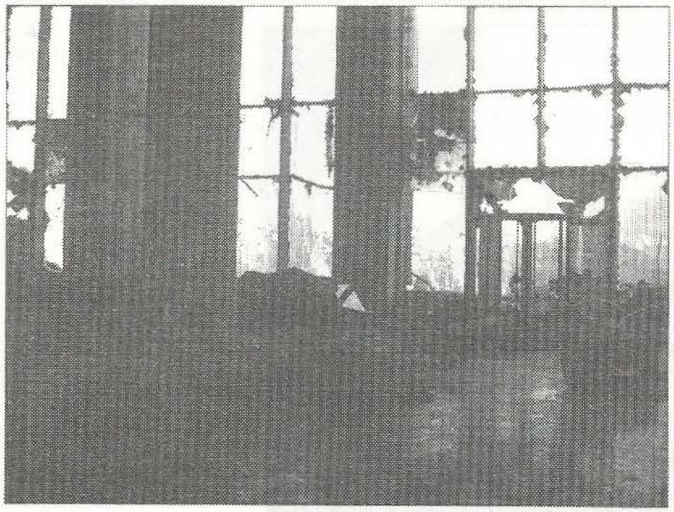


Figure 6-11 Bankers Trust lobby (note debris has been swept into piles).

After the exterior glazing was penetrated by the debris, the dust cloud resulting from the collapse of the towers deposited a layer of dust an inch or more thick throughout the northern part of the building. The 2nd floor lobby area had extensive broken glass, general debris, and dust (Figure 6-11). Figure 6-12 shows a typical office near the collapsed area at the 8th floor.

Although fire sprinkler piping was damaged in the collapse area, causing water to flow on the floor, in general, sprinkler piping throughout other portions of the building remained intact and the building was basically dry. Water pressure in the domestic system was available in upper floors. Ceiling systems generally remained intact, except at the collapsed areas of the building.

6.5 Fireproofing

The structural steel sections were fireproofed with a spray-applied non-asbestos fireproofing material. The thickness on the beam flanges was observed to be on the order of 1/2 inch thick. Many of the rolled steel shapes appeared to be almost completely bare of fireproofing where directly impacted by debris; the remainder of the fireproofing appeared intact even in the damaged areas. Because fires were not ignited in combination with this structural damage, the damaged fireproofing did not affect the performance of the building.

6.6 Overall Assessment

Except for the canopy structure on the north side of the building, which was crushed by falling debris, the building withstood the debris impact well. Excluding the framing and supported floors in the immediate zone of impact and several floors immediately below this area, the structure remained in good condition and serviceable. Repair of the structure should be feasible.

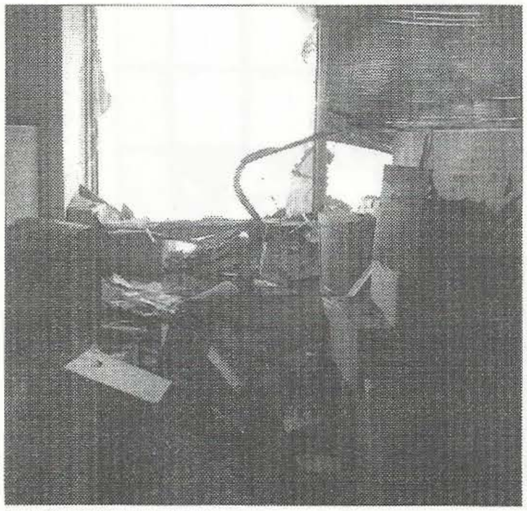


Figure 6-12
Office at the north side of the 8th floor.

6.7 Analysis

A 3-D model was developed to better understand the performance of the building in response to impact from debris and to identify specific design features that contributed to this performance. The model was developed based on information obtained from the following sources: structural drawings (Rudderman 1971–1975), *Draft Structural Engineering Evaluation for the New York Department of Design and Construction (*Nordenson et al. 2001*)*, and personal accounts (Smilow 2001).

All major structural entities were simulated within the ANSYS model: all major framing, intermediate framing in regions of damage, steel decking/slab, columns, and vertical bracing. Given the level of modeling detail required to simulate the behavior of the structure in the regions of damage, three levels of refinement were incorporated within the model to use analytical resources more efficiently:

Level 1: No visible structural damage

Level 2: Local structural damage

Level 3: Partial or imminent collapse

Because there are no eyewitness accounts available that can clarify the order of collapse of portions of the structure, two types of analyses were considered.

Nominally, the final state of the structure could be analyzed to determine the current state of stress redistribution within existing structural members. This analysis clarifies why the damage was arrested.

A more complex analysis could be performed, namely an analysis tracking the partial progression of damage. This type of analysis consists of parametric studies performed to determine the velocity of the impact debris that was required to:

(a) collapse the region of slab between column lines C and D at the 16th through 21st floors;

(b) remove the exterior column D-8 below the 16th floor; and

(c) extend the region of damaged slabs to the two bays bounded by column lines C and E.

These calculations are based on engineering principles and methods. Although they attempt to quantify the extent of the damaged regions, they provide little intrinsic value to the understanding of the building performance. It is highly unlikely the calculations would indicate a unique sequence of events resulting in the observed collapse patterns. Analyses of the surviving structure are much more informative and indicate the redundancy of the steel moment-frame system. These calculations indicate why the collapse was arrested at the 8th floor and why the region of slab loss did not extend beyond the two exterior bays on either side of column line D. Calculations demonstrating the redistribution of load could be performed statically, allowing for inelastic deformations.

Two different types of girder-column moment connections failed as a result of the debris impact, and the performance of these connections had a major effect on the extent of collapse. These two connections were analyzed to better understand their capacity to resist extreme loading. Although the design drawings show some connection information and the observations of the damaged building (Smilow 2001) identified some critical dimensions, there was not enough information to develop detailed finite element models. Therefore, parametric evaluations based on engineering judgment were required to identify the trends in the reserve capacities of these critical connections.

At the time this report was published, a parametric study had been completed to determine the behavior of typical moment connection details in preparation for a subsequent suite of full 3-D frame parametric studies. This suite of calculations was not completed in time for inclusion in this report.

6.7.1 Key Assumptions

Key assumptions were made in the modeling of the building. These assumptions are based on engineering judgment and basic principles of physics:

1. Boundary Conditions:
    a. The structural model was fixed at the base of Concourse Level A.
    b. Vertical rollers were placed at frame 4; given the localization of damage, approximations can be made to model half of the building and restrain the structure a single bay beyond the region of spot damage.
    c. The two-story canopy, north of frame line 8, was excluded from the model; because the structure (frame lines 8 through 10) suffered heavy damage, the collapsed region would not influence the response of the structure in the floors above.
2. Static Nonlinear Analysis:
    a. The nonlinear analysis was performed accounting for large-deflection geometric nonlinearities.
    b. The inelastic response of connections was simulated via nonlinear springs and localized inelastic material properties.
3. Multi-phase Loading:
    a. Application of the gravitational loading.
    b. Removal of missing structure; damaged and missing members were removed in a final-state analysis, and selected members were removed sequentially in an analysis tracking the partial progression of damage.

6.7.2 Model Refinement

Three levels of refinement were incorporated into the model to make more efficient use of the analytical resource for the regions of structural damage. These levels of refinement were developed based on the classification of damage patterns depicted in the draft evaluation prepared by Nordenson (2001) and supplemented by observations of structural damage (Smilow 2001).

In refinement level 1, all major framing was modeled explicitly. All moment and shear connections are assumed to be elastic within regions modeled with this refinement. The steel deck/slab system in conjunction with intermediate framing was modeled using orthotropic plates.

In refinement level 2, all major framing (spandrel beams) was modeled explicitly. Intermediate framing (beams) was not incorporated in the orthotropic plate definition; it was modeled explicitly. All moment connections are modeled explicitly, simulating all spandrel/column connections. All shear connections are assumed to be elastic within regions modeled with this refinement. The steel deck/slab system is not represented explicitly.

In refinement level 3, all major framing (spandrel beams) and intermediate framing (beams) were modeled explicitly. All moment connections and shear connections were modeled explicitly, simulating all spandrel/column connections and beam/spandrel connections, respectively. The steel deck/slab system was not represented explicitly.

Plate elements and beam elements were refined systematically to obtain key output data in regions of heavy damage with correspondingly less refinement farther away from heavy damage areas. In regions modeled using refinement level 3, a minimum of four beam elements were used between columns. The plate elements resting on the beam elements were meshed to match the resolution of the beam elements within this region of refinement. In regions modeled using refinement level 2, a minimum of two beam elements were used between columns.

The plate elements resting on the beam elements were also meshed to match the resolution of the beam elements within this region of refinement. In regions modeled using refinement level 1, single elements were used between columns. This region was modeled to simulate the behavior of regions that were not subjected to structural damage and, because no damage patterns were anticipated, the plate elements in this region of refinement were meshed with minimum discretization.

6.7.3 Simulation of Nonlinear Behavior

The ANSYS model simulates the inelastic response of the structure system by means of nonlinear springs. All moment connections and shear connections in regions of heavy damage (refinement level 3) were modeled using nonlinear rotational and translational springs.

All explicit shear connections were modeled using nonlinear vertical springs. The remaining translational degrees of freedom were assumed to be rigidly constrained. All column splices were assumed to provide continuity based on observations of the structure (Smilow 2001). All explicit moment connections were modeled using nonlinear spring elements. The properties of these nonlinear elements were determined from three-dimensional quasi-static analyses of representative connections, whose response produces a moment rotation relationship. The inelastic response of the connection was simulated by using a elasto-plastic model for the girder, plating, and weld material.

Contrary to the structural drawings, inspection of the floor structure revealed that the steel deck/slab system was not explicitly attached to the supporting spandrel beam elements; it was resting on the underlying spandrel and beam system. This structural assembly was simulated by rigidly constraining the vertical degrees of freedom of the plate elements to the underlying spandrel/beam system. This finite element construct accounted for the transmittal of weight of the deck/slab system, along with additional amounts of reported debris, to the supporting beam elements.

6.7.4 Connection Details

The behavior of a typical fully rigid, partial strength wind-moment connection about the strong axis of the column was studied. The connection of the W18x50 girder to the W14x426 column between girder line 7-8 at frame line D on the 14th floor was modeled as a representative connection. The top and bottom moment plates (estimated as 5/8 inch x 6 inches x 24 inches and 3/8 inch x 10-1/2 inches x 24 inches, respectively) were welded to girder flanges with a 1/4-inch weld. The shear plate (estimated as 5/16 inch x 3 inches x 12 inches) was bolted to each girder web with four 7/8-inch-diameter bolts. Although the design wind moment was estimated to be 2,930 kip-in, the connection capacity was estimated to be 10,800 kip-in.

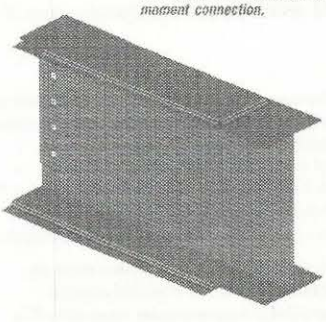
Similarly, the behavior of a typical fully rigid, partial-strength wind-moment connection about the weak axis of the column was studied. The connection of the W24x68 girder to the W14x426 column between girder line C-D at frame line 7 on the 15th floor was modeled as a representative connection. The top and bottom moment plates were estimated as 3/8 inch x 12 inches x 14 inches with a 1/4-inch weld, and the shear in the connection was resisted by a seat, estimated as 1/2 inch x 5 inches x 12 inches, stiffened with a 3/8-inch x 8-inch seat plate. Although the design wind moment was estimated to be 2,830 kip-in, the connection capacity was estimated to be 7,500 kip-in, thus confirming the frame design was governed by stiffness and not strength.

Both connections were modeled in three dimensions in ANSYS, using shell, beam, and continuum elements. All weld material was simulated with a bilinear kinematic hardening material with brittle fracture capabilities at a specified ultimate strain. Figures 6-13 and 6-14 illustrate the details of the finite element models of the two different connection details.

6.7.5 Connection Behavior

Both models were subjected to numerous load combinations to determine the overall behavior of the connection. The weld material was assumed to have a nominal yield strength of 50 ksi. Each model was then subjected to a monotonically increasing moment about the transverse axis of beam bending (M_Y) and the principal strains in the welds were evaluated at the end of each load increment. If the strains in any of the weld elements exceeded the specified ultimate strain, the weld element was considered to have fractured and the modulus of elasticity was reduced by several orders of magnitude. Because the ultimate strain in the weld corresponding to fracture is an unknown quantity, several values were assumed in order to determine the connection behavior. Values of 0.5 percent, 1.0 percent, 10 percent, and 20 percent strain were assumed, and the moment curvature relations for the connection were developed. Based on these calculations, it was observed that the welds fracture before plastic hinges occur when the ultimate strain in the welds is assumed to be less than 1 percent. Furthermore, the connection was observed to degrade very quickly with the onset of weld fracture. The first onset of yielding in the welds was observed at a M_Y value of 1,000 kip-in and 1,400 kip-in. for the shear plate and seat connections, respectively. In the absence of wind moments, the connections were found to be able to support a considerable increase in gravity loads over their dead and live load design values. However, the connection offered little resistance to torsional loads and a significant reduction in capacity of the connection with respect to out of plane bending.

Figure 6-13
3-D ANSYS model of flange and shear plate moment connection.



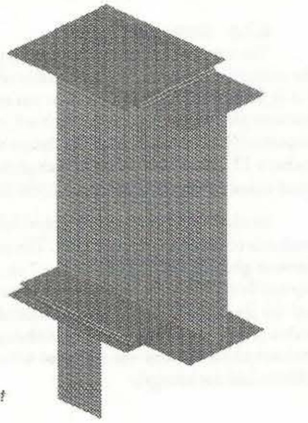


Figure 6-14
3-D ANSYS model of flange and seat moment connection.

The computed results show a sensitivity of the moment curvature relations to the ultimate strain of the weld material and the out-of-plane moments that may have been applied to the connections. The connection sensitivity to out-of-plane and twisting moments significantly influenced the capacity of the connection to resist abnormal loading. The significant reserve capacity of these connections to gravity loads, over an order of magnitude by some estimates, are quickly eroded when the connection is subjected to out-of-plane bending. Therefore, as members were twisted by the collapse of adjacent bays, the connections were less able to withstand the weight of the accumulated debris. This phenomenon may explain why many connections failed and may also explain the sequence of weld fracture. This in turn may have influenced the modes of failure in different connections.

6.8 Observations and Findings

An evaluation of the damage patterns revealed several interesting interpretations. The spandrels were sheared by the impactor, between column lines C and D, from the 23rd to the 19th floors. The D-8 column splices failed at the 18th floor and at the 16th floor, but there are no clues to indicate why column splice tension overload occurred at this location. However, unlike the spandrels above, the girder-column connections at column lines C and D failed. Although severed from the column above and below, column D-8 remained suspended from the girders spanning between column lines E and D. These girders developed large vertical and lateral deformations (twisting). The twisting and bending of these girders may have extended the zone of collapse to bays bounded by column lines C and E. If the column splices had not failed at the 16th and 18th floors, it is possible the extent of collapse may have been limited to the single bay in the path of the impactor. This enlarged zone of damage continued until the collapse was arrested on the 8th floor. It is unlikely that dynamic effects caused the damage to column D-8 below the 16th floor; otherwise, the collapse should have progressed all the way to the ground. It is possible that the column splice failures and the resulting large deformations (twisting) of the spandrels caused the remaining portion of column D-8 to lose lateral bracing, and the collapse was not arrested until the energy of the impactor and debris pile was sufficiently diminished to halt the collapse. If this actually accounted for the enlargement of the damage zone, the restraint of the twisting deformations may have prevented the failure of column D-8.

Although a considerable amount of debris fell from the upper floors onto the first-floor extension to the north, a two-story deep pile of debris accumulated on the 8th floor. By one estimate, although the debris distributed some of its weight by bridging action, the net effect would have been a 500-percent increase in dead load moment for the supporting beam. Based on the computed results, and in the absence of wind, it appears that the connections would have been able to support more than 500 percent of the estimated dead load moments before any hinging would occur. This may explain why multiple stories of debris came to rest at the 8th floor without incurring additional damage to the structure.

Because column D-8 failed below the 16th floor, the beam-to-column moment connection was the single most significant structural feature that helped limit the damage. The portion of the building above the collapsed floors was held in place by frame action of the perimeter. Static elastic analyses of the moment frame show very high stress levels; however, there was a negligible deformation directly above the damaged structure. Furthermore, connections that enable the beams to develop some membrane capacity improve a structure's ability to arrest collapse. The typical floor beam end connections with their A307 bolts were overloaded in direct tension. High-strength bolts would have provided significantly greater tensile ability and possibly held more beams in place through catenary action. Inelastic analyses demonstrate the role of the weaker connections in the response of the structure. Finally, stronger column splices may have made it more difficult for the damaged column to separate from the upper column. Heavier column splices could have allowed the damaged column to function as a hanger and limit the amount of collapsed area, or they could have tended to pull more of the frame down.

6.9 Recommendations

It is difficult to draw conclusions and more detailed study is required to understand how the collapse was halted. As better descriptions of the structural details become available, the observed patterns of damage may provide useful information in the calibration of numerical simulation tools. Some issues requiring further study are:

1. Whether the observed damage in the column flange, and not at the beam flange, of the moment frames top connection plates is due to high restraint in the welds.
2. Why the bottom flange welded connection has typically failed at the fillet weld to beam interface and not at the fillet weld to seat plate interface.
3. The impact response of various moment-connected details.
4. Whether composite construction would reduce local collapse zones. (There were no shear connectors to provide composite action between the floor beams and slab. Composite construction would have increased the capacity of the members and may have dissipated more of the impact energy; however, it may have also pulled a greater extent of the adjoining regions into the collapse zone.)
5. Whether perimeter rebar in the slabs could improve the structural response by providing catenary action and tensile force resistance in the slabs to reduce local collapse zones.
6. Whether the partial-strength connections permitted members to break away from the structure, thereby limiting the extent of damage. (If the moment connections had been designed for the capacity of the sections [as opposed to fully rigid partial strength based on design load and stiffness requirements], the building performance is likely to have been different.)
7. Whether the collapse zone would have been limited if the spandrels on the 16th, 17th, and 18th floors had not been so grossly distorted through twisting.

6.10 References

Guy Nordenson and Associates and Simpson, Gumpertz, and Heger, Inc. 2001. *Draft Structural Engineering Evaluation for the New York Department of Design and Construction (DDC).* Prepared for LZA Technology. October.

Rudderman, James, Office of. 1971–1975. "Bankers Trust Plaza." Structural Drawings. New York, NY.

Smilow, Jeffrey. 2001. Personal account. Cantor Seinuk Group, Inc. New York, NY.

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7 *Peripheral Buildings*

7.1 Introduction

In addition to the WTC buildings and Bankers Trust building, a number of other buildings suffered damage from the projectiles and debris resulting from the deliberate aircraft impacts into WTC 1 and WTC 2 on September 11, 2001, and the resulting collapse of WTC 1, WTC 2, and WTC 7. As discussed in Chapter 1, Section 1.4, on September 12, 2001, the first round of building inspections were contracted for the New York City Department of Buildings (DoB) and the New York City Department of Design and Construction (DDC). This chapter is based on the field observations made by the Building Performance Study (BPS) Team, the Structural Engineers Association of New York (SEAoNY) summary presented below, and *Life Safety Reports* prepared by LAZ Technology/Thornton-Tomasetti (LZA 2001).

The building assessments were compared and coordinated with a parallel inspection performed by DoB and are summarized in Figure 7-1 and Table 7.1 according to the following color coding:

▨	Green	Inspected	No significant damage found.
☐	Yellow	Moderate Damage	Broken glass, façade damage, roof debris.
▨	Blue	Major Damage	Damage to structural members requiring shoring or significant danger to occupants from glass, debris, etc.
▨	Red	Partial Collapse	Building is standing, but a significant portion is collapsed. All of these buildings were inspected and found to have no remaining certifiable structural capacity.
▨	Black	Full Collapse	Building is not standing.

It is important to note the distinction between evaluations for occupancy, access, and life safety and those for structural safety. Extensive damage to glazing and façades may pose a significant threat to the public, but there may be no structural damage. "Major Damage" has both of these types of damage. Because this report is concerned with building performance, primarily structural and fire performance, major damage categories that do not include structural or fire damage are not specifically addressed. The following buildings suffered the most severe collateral damage from the collapse of the WTC towers:

Major Damage (shoring and large debris removal required):

WFC 3, American Express

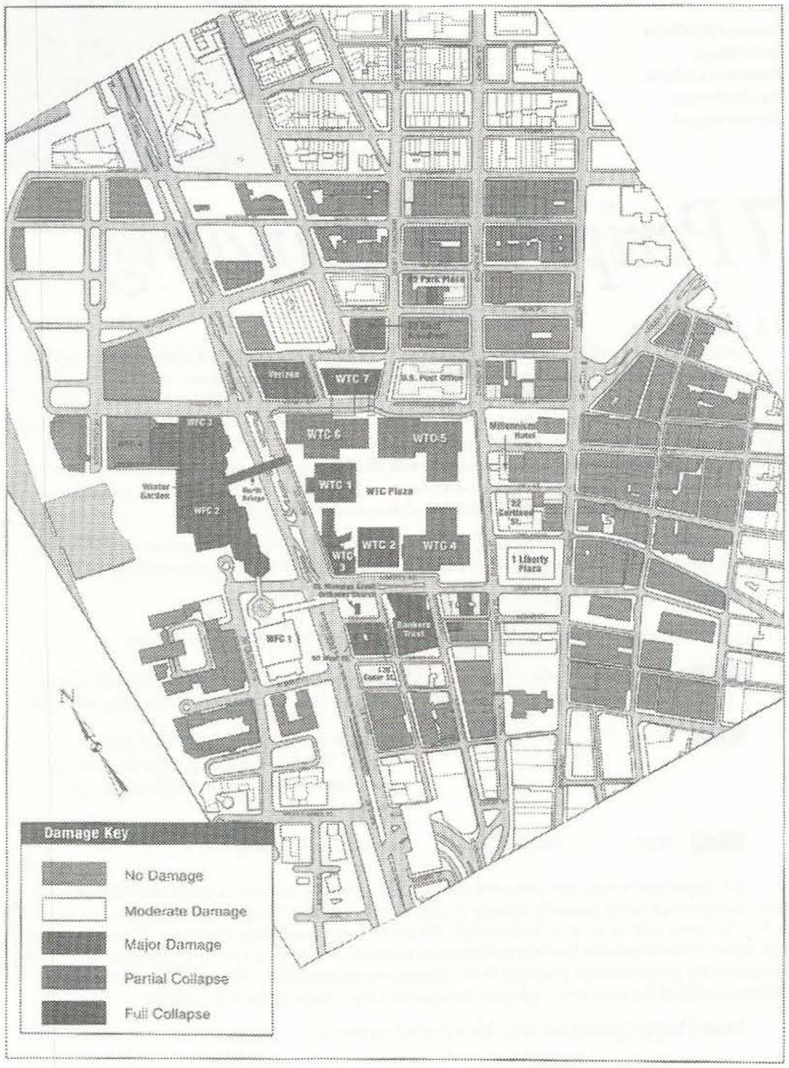
3 Park Place
Verizon
WTC 7
U.S. Post Office
WTC 3
WFC 3
WTC 6
WTC 5
Millennium Hotel
Winter Garden
North Bridge
WTC 1
WTC Plaza
WFC 2
22 Cortlandt St.
WTC 2
WTC 4
WTC 3
1 Liberty Plaza
Bankers Trust
WFC 1
90 West St.
130 Cedar St.
N
Damage Key
No Damage
Moderate Damage
Major Damage
Partial Collapse
Full Collapse

Figure 7-1 New York City DDC/DoB Cooperative Building Damage Assessment Map of November 7, 2001 (based on SEAoNY inspections).

Table 7.1 DoB/SEAoNY Cooperative Building Damage Assessment – November 7, 2001[1]

No.	Block	Lot	Address	Name	Building Color Code[2]	Building Rating
1	16	100	395 South End Ave.	Gateway	Yellow	Moderate Damage
2	16	120	120 West St.	1 WFC Tower A	Yellow	Moderate Damage
3	16	120	120 West St.	South Bridge	Yellow	Moderate Damage
4	16	120	120 West St.	1-2 WFC Link Bridge	Yellow	Moderate Damage
5	16	125	125 West St.	2 WFC Tower B	Blue	Major Damage
6	16	140	200 Vesey St.	3 WFC Tower C - Annex	Blue	Major Damage
7	16	140	201 Vesey St.	Winter Garden Building	Blue	Major Damage
8	45	1	2 Wall St.		Yellow	Moderate Damage
9	49	2	111 Broadway		Yellow	Moderate Damage
10	51	14	125 Greenwich St.		Yellow	Moderate Damage
11	51	15	90 Trinity Pl.		Yellow	Moderate Damage
12	52	10	120 Cedar St.		Blue	Major Damage
13	52	15	110 Trinity Pl.		Yellow	Moderate Damage
14	52	21	120 Liberty St.		Yellow	Moderate Damage
15	52	22	124 Liberty St.	Fire Station	Yellow	Moderate Damage
16	52	30	106 Liberty St.		Yellow	Moderate Damage
17	52	7501	110 Liberty St.		Yellow	Moderate Damage
18	52	7502	114 Liberty St.	Engineering Building	Blue	Major Damage
19	53	23	5 Carlisle		Yellow	Moderate Damage
20	53	28	1 Carlisle		Yellow	Moderate Damage
21	53	33	110 Greenwich St.		Yellow	Moderate Damage
22	54	1	130 Liberty St.	Bankers Trust	Blue	Major Damage
23	56	1	130 Cedar St.		Blue	Major Damage
24	56	20	155 Cedar St.	Greek Orthodox Church	Black	Collapse
25	56	4	90 West St.		Blue	Major Damage
26	58		WTC 1	North Tower	Black	Collapse
27	58		WTC 2	South Tower	Black	Collapse
28	58		WTC 3	Marriott International Hotel	Black	Collapse
29	58	1	WTC 4	South East Plaza		Partial Collapse
30	58	1	WTC 5	North East Plaza		Partial Collapse
31	58	1	WTC 6	Custom House		Partial Collapse
32	84		WTC 7		Black	Collapse
33	62	1	1 Liberty Plaza		Yellow	Moderate Damage
34	63	1	10 Cortland St.		Yellow	Moderate Damage
35	63	3	22 Cortland St.		Yellow	Moderate Damage
36	63	6	27 Church St.	Century 21	Yellow	Moderate Damage
37	63	13	189 Broadway		Yellow	Moderate Damage
38	63	15	187 Broadway		Yellow	Moderate Damage
39	65	10	9 Maiden Ln.	Jeweler's Building	Yellow	Moderate Damage
40	65	16	174 Broadway		Yellow	Moderate Damage
41	80	4	47 Church St.	Millennium Hotel	Yellow	Moderate Damage
42	84	1	140 West St.	Verizon	Blue	Major Damage
43	86	1	90 Church St.	Post Office	Yellow	Moderate Damage
44	88	2	12 Vesey St.		Yellow	Moderate Damage
45	88	8	26 Vesey St.		Yellow	Moderate Damage
46	86	10	26 Vesey St.		Yellow	Moderate Damage
47	86	13	14 Barclay St.		Yellow	Moderate Damage
48	125	20	100 Church St.		Yellow	Moderate Damage
49	126	2	110 Church St.		Yellow	Moderate Damage
50	126	9	45 Park Pl.		Blue	Major Damage
51	126	27	120 Church St.		Yellow	Moderate Damage
52	127	1	30 West Broadway		Blue	Major Damage
53	127	18	75 Park Pl.		Yellow	Moderate Damage
54	128	2	224 Greenwich St.		Yellow	Moderate Damage
55	136	15	50 Warren St.		Yellow	Moderate Damage
56	136	16	128 Chambers St.		Yellow	Moderate Damage

[1] Adapted from SEAoNY inspections of September and October 2001 -- Building Ratings and Actions table.

[2] Based on DDC/SEAoNY inspections of September and October 2001 and DoB inspections of October 22, 2001.

Verizon
30 West Broadway
45 Park Place
Bankers Trust
90 West Street
130 Cedar Street

Partial Collapse

WTC 4
WTC 5
WTC 6
Winter Garden building (later revised to Major Damage)

Full Collapse

WTC 3
WTC 7
North Bridge from Winter Garden to WTC 1
St. Nicholas Greek Orthodox Church

Damage to the WTC and Bankers Trust buildings has been covered in previous chapters, and no inspection was made of St. Nicholas Greek Orthodox Church, because it was completely destroyed by falling debris. The damage to and performance of the remaining buildings is briefly presented. Immediately after the collapse of the towers, One Liberty Plaza was reported to be near collapse, but was later found to have no structural damage. The events leading up to this misunderstanding are briefly discussed.

7.2 World Financial Center

The World Financial Center (WFC) complex is located immediately west of the WTC Plaza, and includes four office towers, pedestrian walkways, and the Winter Garden (Figure 7-1). The buildings are of contemporary construction dating from 1985 to the present, have large floor plans, and are steel-framed structures with granite-clad curtain wall facades.

These buildings sustained varying degrees of façade and structural damage from the debris, with the eastern elevations experiencing the heaviest damages. The north and south elevations sustained lesser debris damage. WFC 1, 2, and 3 suffered glazing and façade damage, but WFC 4 was undamaged. Debris and dust penetrated nearly the full floor areas of WFC 2 and WFC 3 at several levels.

7.2.1 The Winter Garden

The Winter Garden lies between WFC 2 and WFC 3. It is a large greenhouse structure with a glass and steel telescopic barrel vault roof and is one of the largest public spaces in New York. The structure covers an area of approximately 200 feet by 270 feet and includes a public space of 120 feet by 270 feet. The largest vault has a clear height of about 130 feet and a span of 110 feet. The west elevation is made entirely of glass panels. The east end of the building has five composite steel floors that support a glass dome that covers a ceremonial stair. The structure has expansion joints where it meets WFC 2 and WFC 3. The spatial stability of the frame is insured by trussed arch framing. The east end was linked to the WTC complex by the North Bridge, which had a 200-foot clear span and was 40 feet wide. The west end has an entrance door.

Columns from WTC 1 hit the east end of the structure, particularly the area directly adjacent to the North Bridge. The Winter Garden experienced severe collapse of the eastern end framing. Several other semicircular trusses and parts of the dome were also badly damaged. The western two bays of the roof structure remained intact, but were covered with debris. Inspectors estimated that 60 percent of the roofing glass panels of the structure had collapsed.

Additional structural collapse occurred on parts of the 2nd and 3rd floor framing adjacent to WFC 2 and WFC 3, the North Bridge connection extension, the ceremonial stair above the circular landing, and the 4th and 5th floors at the eastern end. Localized structural collapse occurred in various other areas of the barrel roof.

As the eastern roof trusses were sheared in several places, support was provided only by the transverse plate girders that remained in place. These conditions, coupled with the shearing of trussed arch framing, led the first round of inspectors to conclude that the structure was potentially unstable, and a rating of Partial Collapse was assigned. After installation of shoring, a new evaluation of the building led engineers to determine that the building was repairable, and the rating was revised to Major Damage.

7.2.2 WFC 3, American Express Building

The 50-story WFC 3 building has a plan area of approximately 200 feet by 250 feet. Exterior column trees from WTC 1 were found hanging from the southeast corner of WFC 3 (Figure 7-2) and on the setback roof and against the east face of the Winter Garden (Figures 7-3 and 7-4). The impact of exterior column trees caused structural damage in both structures. Building faces not directly oriented toward the WTC site suffered minimal damage, even at the close proximity of several hundred yards.

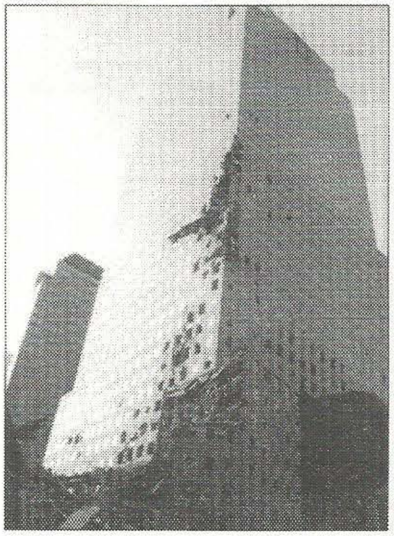

Figure 7-2
Southeast corner of WFC 3.

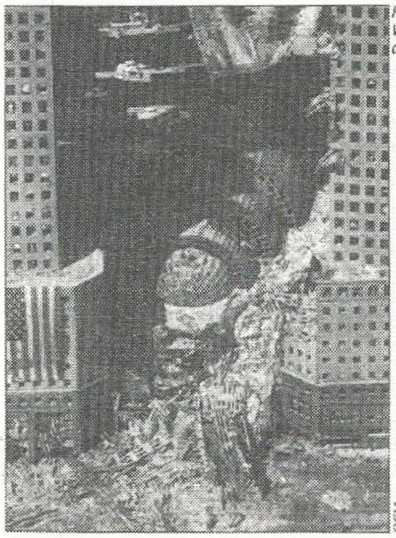

Figure 7-3
View of Winter Garden damage from West Street, with WTC 1 debris in front of WFC 2.

OEM

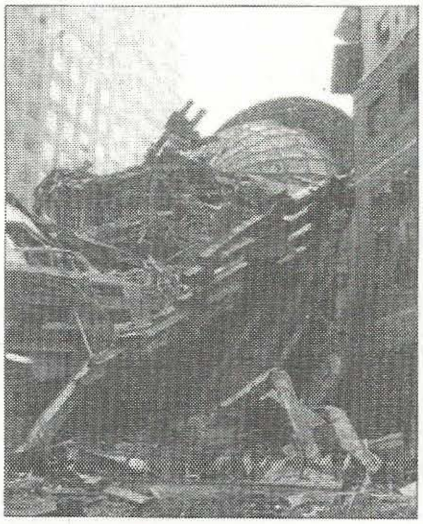

Figure 7-4
View of Winter Garden damage from West Street, with WTC 1 debris leaning against WFC 3.

The glazing and façade damage in the building was similar to that found in WFC 1 and WFC 2, which also had extensive cracking and breakage of glazing and granite panels. Debris from WTC 1 caused a collapse of the top 8 stories of the 10-story octagonal extension located at the southeast side of the building. The main WFC 3 building suffered damage from floors 17 to 26. A three-story section of exterior column trees from WTC 1 hung from the base of the collapsed area at floor 20, as shown in Figure 7-2, with approximately 25 feet of the column hanging outside the building. At floors 17 through 26, the corner column had been removed by the impact of debris, and the floors cantilevered from adjacent columns to the north and west. Smaller column debris penetrated floor 17. The damage did not extend past the corner bay, which had to be shored and was later demolished.

Interior damage is shown in Figure 7-5. Inspection of the interior determined that steel framing members that sustained direct impact from large debris had significant portions of the cementitious fireproofing material knocked off. The fireproofing was intact on adjacent steel members that had not been directly hit.

The localized nature of the damage, given the size of projectiles that impacted the building, is notable. Observations noted small welds between column end bearing plates at exterior and interior columns, indicating the columns near the damage zone were designed for gravity loads, and tension loads from wind were not a critical design parameter. This type of connection between columns may have allowed a column member to be knocked out of place without causing substantial displacement or damage to connecting framing.

7.3 Verizon Building

The Verizon building is located on the block bounded by Barclay Street on the north, Washington Street on the east, Vesey Street on the south, and West Street on the west. It is north of WTC 1 and WTC 2, and immediately west of WTC 7, which all collapsed.

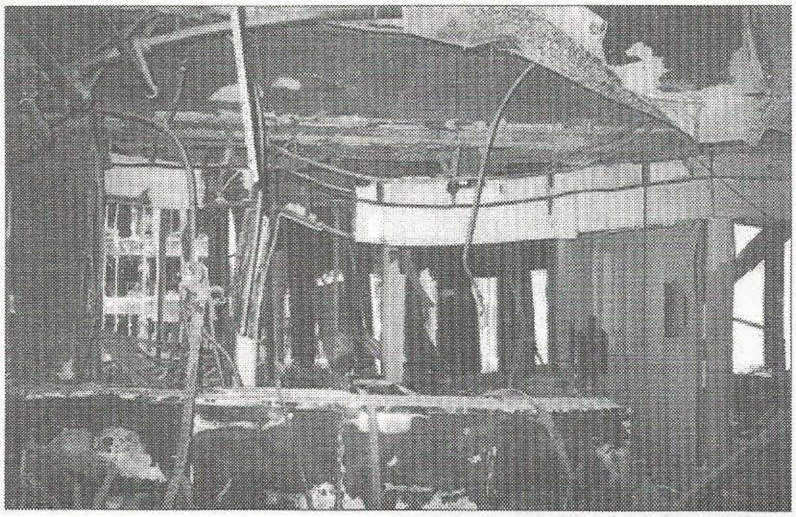

Figure 7-5 Interior damage at floor 20 of WFC 3.

The 30-story Verizon building was built in the 1930s and has a steel frame with infill exterior walls of unreinforced masonry, and five basement levels. The steel frame is encased in cinder-concrete and draped-wire-mesh, with cinder-concrete slab floor construction. Beams are rolled sections (mostly 12 inches deep) with cover plates at floors with high live loads. Girders are either rolled sections or built up from plates and angles. Columns are also built-up sections. Partially restrained moment frames at the building perimeter provide lateral resistance. The masonry walls are about 12 inches thick (on average), and the columns are encased in brick. The façade and 1st floor lobby are registered as historic landmarks. At the time of the adjacent building collapses, the Verizon building was in the midst of an extensive façade restoration program.

The proximity of the building to WTC 2 resulted in considerable damage to the south and east faces of the building. Damage included collapsed floor slabs and deformed beams and columns, including some local buckling. Window damage was moderate, and it is notable that the windows contained wire mesh. The west (West Street) and north (Barclay Street) sides of the building were not damaged.

The east (Washington Street) side of the building was damaged from about the 9th floor down, primarily due to the impact of debris sliding out from the base of WTC 7 (Figures 7-6, 7-7, and 7-8). Some damage may have also been caused by WTC 1 debris. In addition to fairly extensive façade damage (bricks and windows), there was damage to two bays of slab and framing at the 1st, 4th, and 7th floors and to one bay of slab and framing (including spandrel beam) at the 1st floor mezzanine and at the 5th floor. Two exterior columns suffered major damage between the 1st and 2nd floors (Figure 7-9), one exterior column suffered minor damage between the 3rd and 5th floors, and two exterior columns suffered major damage between the 6th and 8th floors. In addition, one interior column suffered minor damage below the 7th floor.

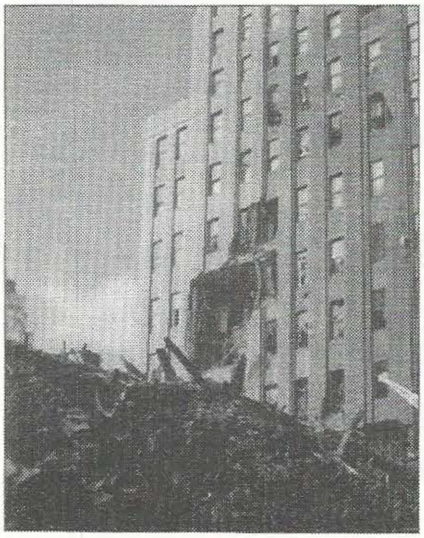

Figure 7-6
Verizon building – damage to east elevation (Washington Street).

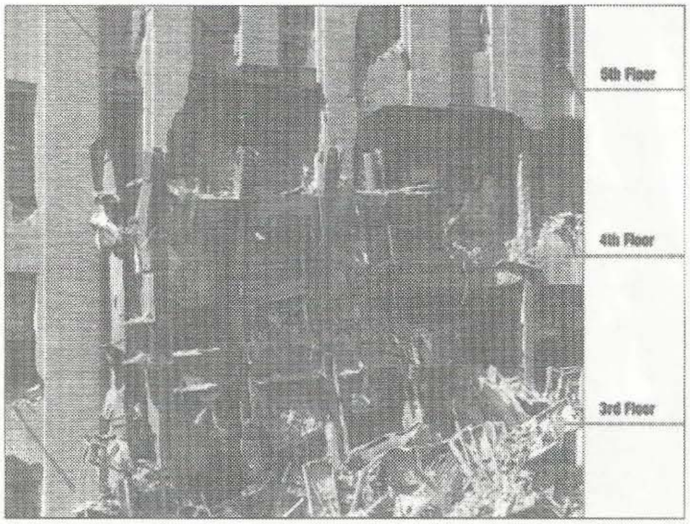
5th Floor
4th Floor
3rd Floor

Figure 7-7 Verizon building – damage to east elevation (Washington Street) due to WTC 7 framing leaning against the building.

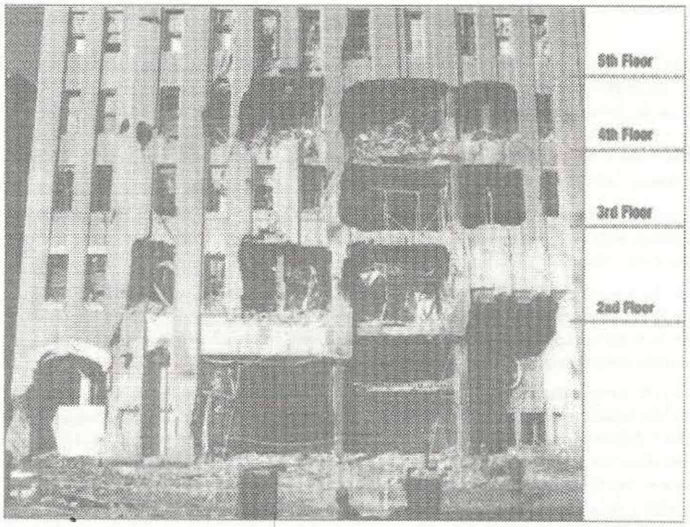
5th Floor
4th Floor
3rd Floor
2nd Floor

Figure 7-8 Verizon building – damage to east elevation (Washington Street).

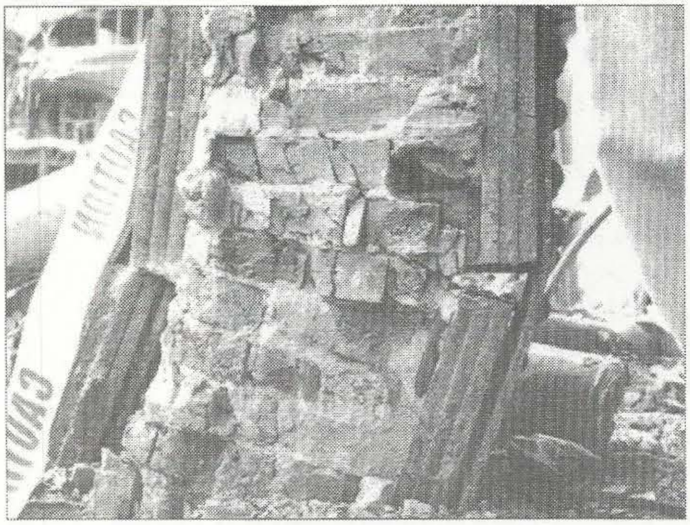

Figure 7-9 Verizon building – column damage on east elevation (Washington Street).

The south (Vesey Street) side of the building was damaged from approximately the 13th floor down, primarily due to the impact of projectile debris from the collapse of WTC 1 (Figure 7-10). In addition to fairly extensive façade damage (bricks and windows), two bays of slab and framing were damaged at the sidewalk arcade at the 1st floor, and one bay of slab and framing (including spandrel beams) was damaged at the 6th, 7th, 9th, 11th, 12th, and 13th floors (Figures 7–11 and 7-12). In addition, one interior column suffered minor damage below the 1st floor.

None of the damage to the floor framing threatened the structural integrity of the building. Although the damaged columns were deflected out-of-plane, it was determined that the columns were stable and not in danger of imminent collapse.

In general, the Verizon building performed well, especially given its close proximity to WTC 7. On the south (Vesey Street) side of the building, damage was extremely localized near the point of impact of projectile debris. In some cases, only a short section of spandrel beam and small area of floor slab were damaged, leaving the remainder of the structural bay intact (Figure 7-12).

On the east (Washington Street) side of the building, most of the damage appeared to be due to the lateral pressure of the spreading debris at the base of WTC 7 (Figure 7-7). Two of the columns between the 1st and 2nd floors were deflected into the building by as much as 2 feet (with most of the rotation occurring at the column splice just above the 1st floor): at one of the columns, very little contact remained at the column splice (Figure 7-9). Even so, the columns did not buckle, and structural bays above did not collapse or deflect significantly. Similarly, the structural bays supported by the column between the 6th and 8th floors that was completely destroyed by the impact of projectile debris were essentially undamaged.

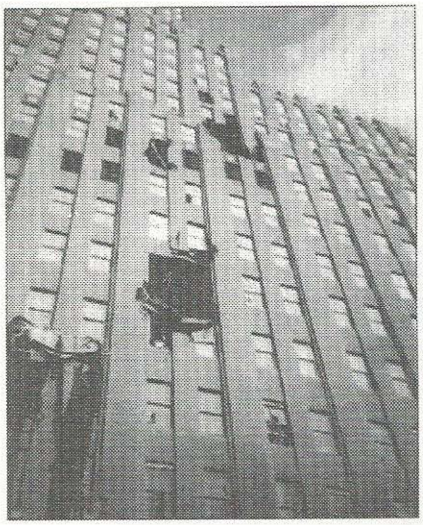

Figure 7-10
Verizon building – damage to south elevation (Vesey Street).

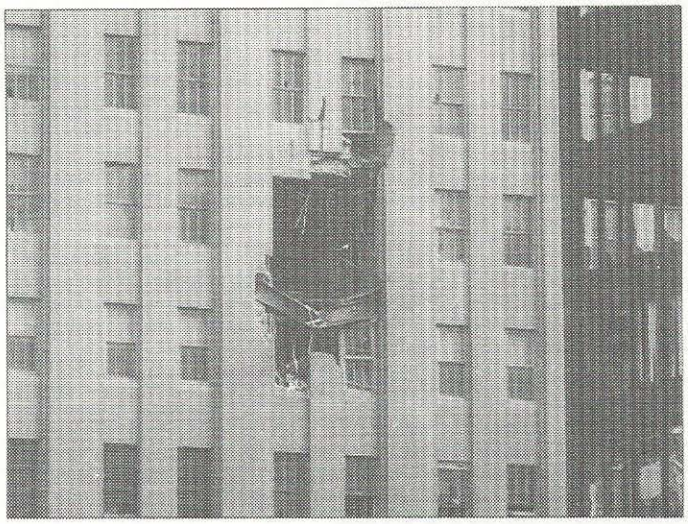

Figure 7-11 Verizon building – localized damage to south elevation (Vesey Street).

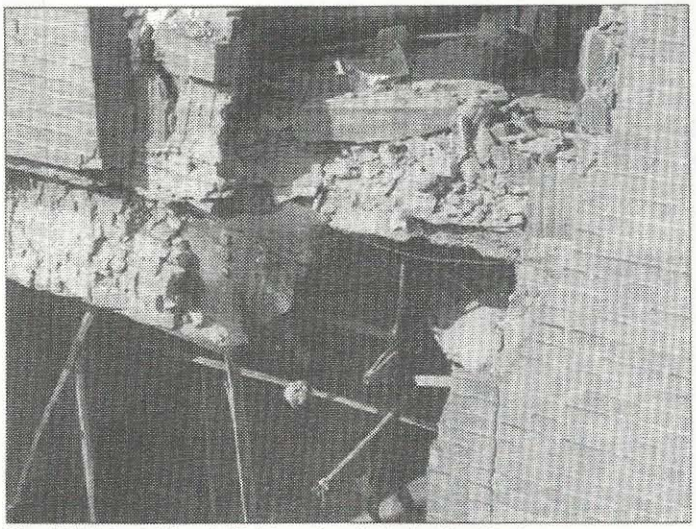

Figure 7-12 Verizon building – detail of damage to south elevation (Vesey Street).

Several factors may have contributed to the performance of the Verizon building. The thick masonry walls, brick-encased columns, and cinder-concrete-encased beams and girders probably absorbed much of the energy of the impacts while also providing additional stiffness and strength to the building frame. The lower floors (up to the 10th floor) were designed for either 150 pounds per square foot (psf) or 275 psf, depending on the intended occupancy. Consequently, the member sizes and end connections are unusually stocky. Although designed for higher-than-normal live loads, at the time of the adjacent building collapses, actual live loads were relatively low.

Most floors are framed with 12-inch-deep beams with cover plates, presumably to maintain uniform floor clearances. These sections had full lateral bracing and were probably able to develop close to their full plastic capacities without buckling. Almost every beam-column connection was nominally moment-resistant, making the structural system highly redundant. All of these characteristics combined to both absorb the energy of the debris impacts and provide alternate load paths around the damaged areas.

The performance of this building led to several observations. The original design was for a substantially heavier live load and use as a telephone switching facility. Even so, the exterior columns on the east side were substantially damaged at the lower floors by the collapse of WTC 7. The nominally 12-inch thick brick masonry perimeter walls absorbed a significant portion of the impact energy, resulting in less damage to the structural steel framing. Impact damage was localized and did not propagate beyond immediate points of impact (sometimes not even full bays were damaged). It was noted that the windows performed better than those in other peripheral buildings, likely due to the wire mesh.

7.4 30 West Broadway

The office structure at 30 West Broadway is most recently known as Fiterman Hall of the Borough of Manhattan Community College campus of the City University of New York. It is located just north of WTC 7. The 17-story building was constructed in the 1950s and has a concrete-encased structural steel frame with cinder-concrete floor slabs with draped steel mesh. The structure had riveted, bolted, and welded connections, and roof setbacks at the 6th and 15th floor levels. The curtain wall consists of horizontal bands of windows over glazed brick. There are continuous lintels at every floor. The building was in the final stages of rehabilitation work at the time of the terrorist attacks.

The southern half of the west façade and most of the south façade were severely damaged or destroyed. The south face of the building suffered structural damage in the exterior bay from impact by large debris from WTC 7 (Figure 7-13). There was no damage to the east and north faces of the building, and no fire in the building, even though there was a substantial fire in WTC 7.

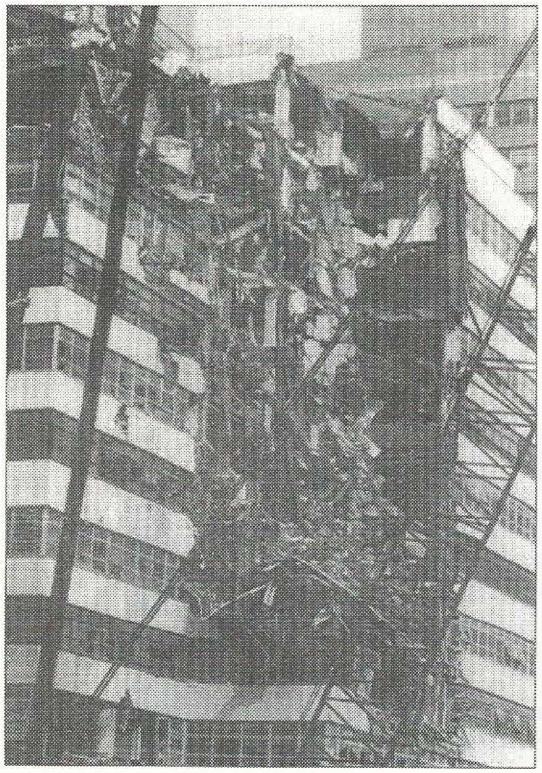

Figure 7-13
30 West Broadway – south façade, 6th floor to roof, looking northeast.

Damage was concentrated along the south face at and below the setback at the 15th floor. Portions of the south façade from the 15th floor collapsed. A vertical section of the perimeter wall extending five floors down from the setback at the center of the south façade was raked away. Local collapse also occurred at the southwest corner. The majority of the glass panes were knocked out on the south façade, in a triangular pattern that extended to the full width of the base. The south side of the building was unstable and required bracing. Floors 9 through 14 had two collapsed bays, and floors 3 through 6 had up to three collapsed bays. No structural damage was observed one bay away from the impact damage.

Floors 9 through 14 had at least two collapsed exterior bays and floors 3 through 6 had at least three collapsed exterior bays. There was relatively little damage at the 7th floor. A considerable amount of debris was on the 8th floor. The steel beams supporting two bays of this floor yielded, but are still in place.

The building was impacted by debris from the collapse of WTC 7. Although structural damage from debris impact was contained to the exterior bays on the south side of the building and between roof setback levels, it was more extensive than that observed on the east side of the Verizon building.

7.5 130 Cedar Street

Constructed in the 1930s, the building at 130 Cedar Street is a 12-story reinforced concrete frame structure with setbacks at the 10th, 11th, and 12th floors (Figure 7-14). The building is directly east of 90 West Street and is bordered by Cedar Street to the north, Washington Street to the east, and Albany Street to the south.

The floor framing consists of reinforced concrete flat slabs supported on square columns with capitals and dropped slabs. Columns are spaced at approximately 16 feet on center in the east-west direction and approximately 21 feet on center in the north-south direction. Perimeter concrete spandrel beams beneath the windows and interior infill walls of brick, terra cotta, or concrete masonry provide additional lateral stiffness.

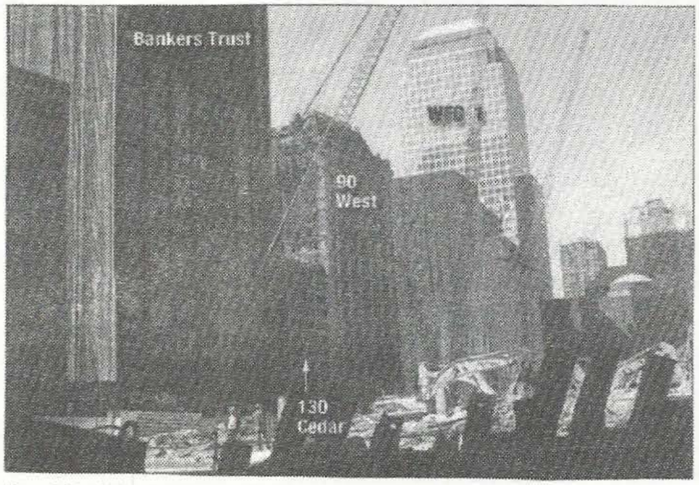

Figure 7-14 130 Cedar Street and 90 West Street.

Some façade damage was noted (primarily to the parapets), but most of the damage occurred at the roof level where the slab of the northeast corner collapsed under debris with the column capitals punching through the slab. A column section from WTC 2 penetrated the 10th floor roof slab. The southern portion of the building was not damaged. Structural damage from projectile impact and fire occurred primarily above the 9th floor. Fire damage was evident on the 11th and 12th floors in the northwest corner. Several concrete columns were cracked, possibly from the impact. Several bays at the northeast corner were severely damaged from debris impact. Concrete samples from two fire locations indicated that the concrete structure may have experienced fire temperatures of between 315 °C (600 °F) and 590 °C (1,100 °F). Spalling of capitals was observed in the fire areas.

The masonry infill walls were cracked throughout the building. It is not clear whether the condition pre-existed, or if it was due to the fire, floor settlement, or frame movement.

7.6 90 West Street

This building is located south of the WTC site, and adjacent to the 130 Cedar Street building located on the west side, as shown in Figure 7-14. The 24-story building has a steel-frame structure with a terra cotta flat-arch floor system and infill walls of unreinforced masonry. It was designed by architect Cass Gilbert and structural engineer Gunvald Aus in 1907. The floor plan has a skewed "C" configuration, with overall dimensions of approximately 124 feet by 180 feet. At the higher floors, the typical exterior wall assembly is terra cotta tiles on a brick wall. This building is a designated New York City landmark. In 1907, the building towered over the waterfront and warehouses in the area. Its top floor had a restaurant that was billed as the "world's highest."

The riveted steel framing consists of rolled and built-up sections for the columns and beams. Columns are spaced approximately 18 feet apart. The primary framing runs north-south, with secondary members in the east-west direction. Lateral load resistance is provided primarily by partial-strength, partially restrained moment connections of frame members and the infill masonry walls. The floor slabs of terra cotta flat arches appeared to be topped with low-strength cinder-concrete. Terra cotta and masonry enclosures provided fireproofing for all original architectural areas and structural elements. The building construction is shown in Figure 7-15

The New York City Building Code required the floors to be tested for 4 hours while exposed to a fire maintained at 927 °C (1,700 °F) and a load of 150 psf. Following the fire test, the fire-exposed underside was exposed to a fire hose stream with a nozzle pressure of 60 pounds per square inch (psi) for 10 minutes. The floor was then loaded and unloaded with a uniform load of 600 psf in the middle bay. The test was considered successful if the deflection of the beams supporting the assembly was less than 2.5 inches over a 14-foot length, after cooling.

The building was undergoing façade rehabilitation and was fully covered with scaffolding. Many of the interior columns still had the original terra cotta covers, and some were covered with plaster, but others were covered with sheet rock and intumescent paint, and, at one location, there was a metal deck with spray-on fireproofing. In some locations, spray-on cementitious fireproofing was used for later tenant work. Some scaffolding planks caught fire and may have contributed to the spread of the fire between floors.

Terra cotta and hollow-clay tile arches were common in fireproof office construction. Most of them were patented systems with 6- to 15-inch depths and spans from 54 to 90 inches. The arches were supported on the bottom flanges of steel beams. The bottom flanges of the supporting steel beams were generally protected by clay tile or terra cotta fireproofing. To provide a smooth finish, the arches were usually topped with a cementitious material that also protected the haunches of the steel beams. The arches had tie rods to resist the thrust of the arch. An 8-inch flat arch with hollow tile and a span of 6 feet could carry a safe load of

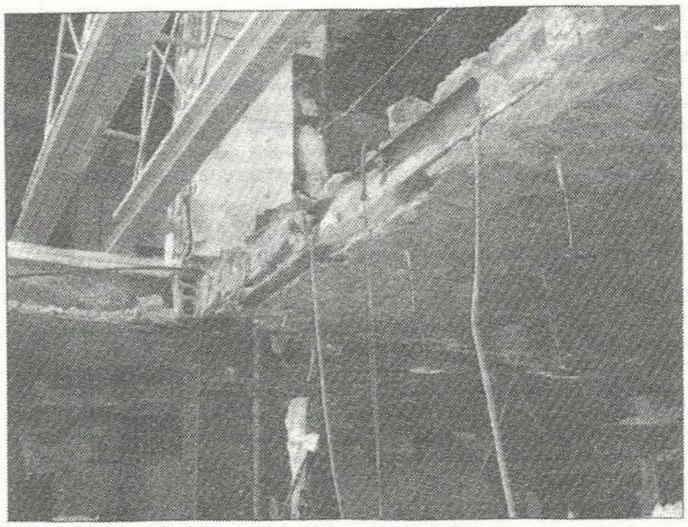

Figure 7-15 Interior of 90 West Street showing typical construction features.

170 psf (Kidder 1936). At 90 West Street, the tile floor arches usually span 6 feet. At lower floors, the tiles have a 12-inch thickness and cover the bottom flanges of the beams.

The roof was damaged by debris falling from WTC 2, and approximately half of the north face of the building experienced projectile impact and fire damage. WTC 2 projectiles severed spandrel beams at floors 8 to 11 in the 2nd bay from the west end, and in a middle bay at the 6th floor. Terra cotta slabs were damaged mostly in the exterior bay at these locations. In general, the projectiles damaged only the masonry and broke many terra cotta features. The damage to the interior structural terra cotta floor slabs was primarily due to the brittle fracture of the terra cotta slabs upon impact by large debris. Most of the damage was restricted to the two northernmost bays, with the exception of fire damage on the 1st through 5th, 7th through 10th, 14th, 21st, and 23rd floors. The fire did not spread to the south side of the building, except for the first 4 floors. Columns were buckled 1-2 inches on the 8th and 23rd floors, approximately a foot below the ceiling, as shown in Figures 7-16 and 7-17. A tube column supporting a north exit stair from the roof and a built-up column supporting the roof were the only other heat-induced buckling damage observed during initial inspections.

This type of construction, with terra cotta tiles providing fire protection, was common in early 20th century construction. The style of construction resulted in a highly compartmentalized building, which may have helped slow the spread of fire. The Fire Department of New York was able to control the fires in this building. The fire damage observed in the building, with minimal structural damage from a normal fire load, is considered typical for this type of construction and fire protection; however, it has been suggested that the scaffolding that was in place for renovations contributed to the spread of fire between floors that may not have occurred otherwise. However, the only structural damage observed was buckling damage near the tops of two columns.

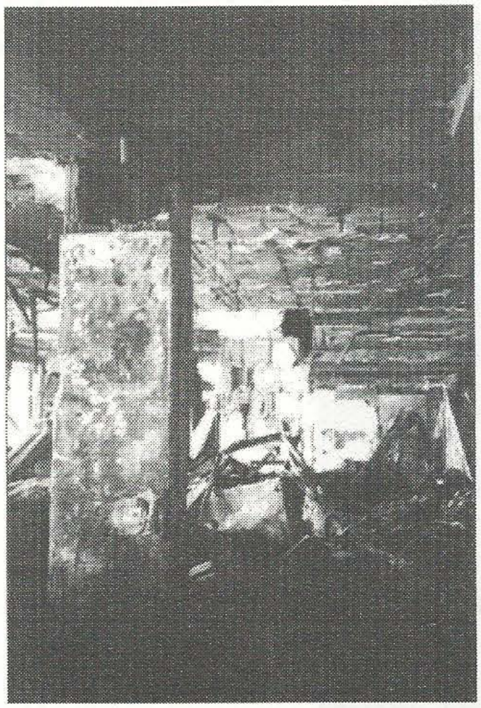

Figure 7-16
Buckling damage at top of column on floor 8 of 90 West Street. Note the loss of fire protection at the top of the column.

7.7 45 Park Place

This building is located three blocks north of the WTC site (Figure 7-1), and was initially rated as No Damage when inspected from the exterior. However, subsequent interior inspection revealed that three floor beams were missing from the top story of the building as a result of the landing gear that penetrated the roof following the airplane impact on WTC 2, shown in Figure 1-4 (in Chapter 1). The rating was subsequently changed to Major Damage. No other significant damage was found.

7.8 One Liberty Plaza

One Liberty Plaza (One Liberty) is a 54-story, 730-foot-high building, comprising a footprint of 238 feet in the north-south direction by 163 feet in the east-west direction. The building area is approximately 2,000,000 square feet (Figures 7-18 and 7-19). It was designed by Skidmore, Owings, and Merrill in 1970 and served as corporate headquarters for U. S. Steel Corporation.

During the afternoon of September 11, following collapse of WTC 1 and WTC 2, rumors were spread that One Liberty was in imminent danger of collapse. This was due to a report by an untrained observer that the building face appeared to be moving or leaning.

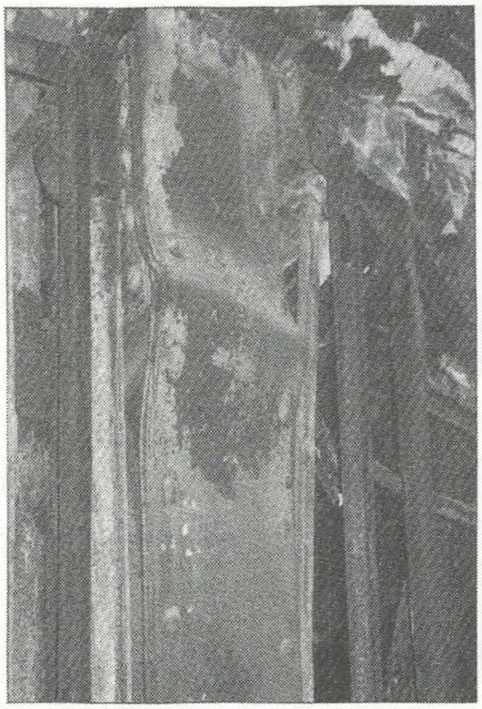

Figure 7-17
Buckling damage at top of column on floor 23 of 90 West Street.

The majority of damage incurred at One Liberty consisted of broken window glass and frames. Most of that broken glass was in the lower six floors of the west-facing elevation, with less breakage on the floors above. There was, however, some broken glass on the north- and south-facing elevations as well. At those elevations, most of the broken glass was located at floors 1 through 6. There were approximately 550 broken lites of glass, and approximately 200 frames were damaged beyond repair.

On September 12, there was a persistent rumor that One Liberty was still in danger of collapse. The building was inspected by structural engineers conducting building surveys and safety evaluations of buildings around the WTC site. The building vertical alignment was measured with a transit to determine whether any lateral drift had occurred along the height of the building. Three locations on the west face were evaluated, and no apparent movement was observed in the building. The One Liberty Plaza building was determined to be safe, except for dangers related to broken glass.

Statements were released about the safety of the building, but the rumors persisted on September 13. To stop the rumors and convince the public of the building's safety, DDC surveyors continuously monitored the building and engineers inspected each floor. When a piece of glass fell off One Liberty during the

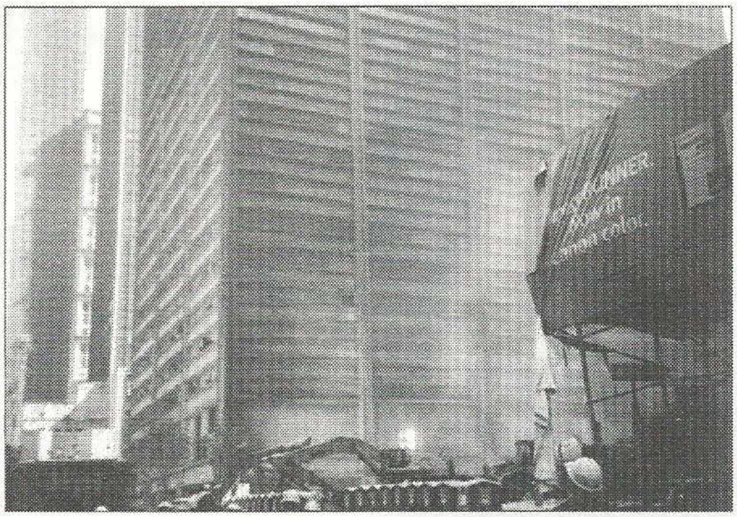

Figure 7-18 One Liberty Plaza – south elevation, lower floors.

afternoon, it was rumored to be a partial collapse. The findings of the engineers and surveyors concerning the structural safety of One Liberty were reported on the nightly news, and the rumors stopped.

7.9 Observations and Findings

Steel-frame construction from the 1900s through the 1980s, though different in many details, performed well under significant impact loads by limiting impact damage and progressive collapse to local areas.

Heavy unreinforced masonry façades were observed to absorb significant amounts of impact energy in the Verizon and 90 West Street buildings. Heavy masonry façades like those in the Verizon, 90 West Street, or even 130 Cedar Street buildings may also provide an alternative load path for a damaged structure.

Older, early-century fireproofing methods of concrete-, brick-, and terra cotta tile-encased steel frames performed well, even after 90+ years, and protected the 90 West Street building from extensive structural damage.

7.10 Recommendations

The known data and conditions of the perimeter structures after the impact damage should be utilized as a basis for calibration, comparison, and verification of existing software intended to predict such behavior, and for the development of new software for the prediction of the ability of structures to sustain localized and global overload conditions.

7.11 References

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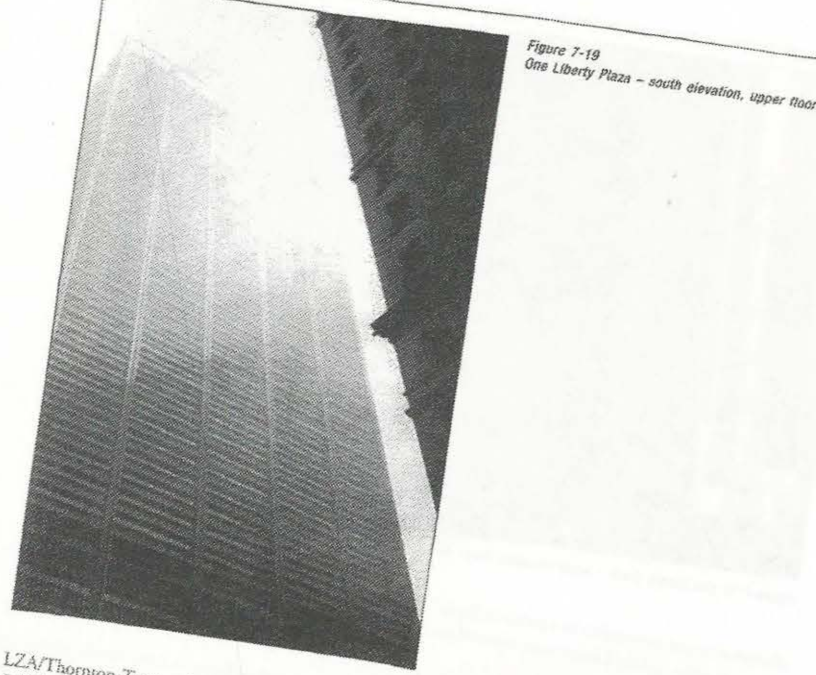

Figure 7-19
One Liberty Plaza – south elevation, upper floors.

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8 Observations, Findings, and Recommendations

The observations, findings, and recommendations of this building performance study are summarized in three sections:

- Summary of Report Observations, Findings, and Recommendations
- Chapter Observations, Findings, and Recommendations
- Building Performance Study (BPS) Recommendations for Future Studies

8.1 Summary of Report Observations, Findings, and Recommendations

In the study of the WTC towers and the surrounding buildings that were subsequently damaged by falling debris and fire, several issues were found to be critical to the observed building performance in one or more buildings.

These issues fall into several broad topics that should be considered for buildings that are being evaluated or designed for extreme events. It may be that some of these issues should be considered for all buildings; however, additional studies are required before general recommendations, if any, can be made for all buildings. The issues identified from this study of damaged buildings in or near the WTC site have been summarized into the following points:

a. Structural framing systems need redundancy and/or robustness, so that alternative paths or additional capacity are available for transmitting loads when building damage occurs.

b. Fireproofing needs to adhere under impact and fire conditions that deform steel members, so that the coatings remain on the steel and provide the intended protection.

c. Connection performance under impact loads and during fire loads needs to be analytically understood and quantified for improved design capabilities and performance as critical components in structural frames.

d. Fire protection ratings that include the use of sprinklers in buildings require a reliable and redundant water supply. If the water supply is interrupted, the assumed fire protection is greatly reduced.

e. Egress systems currently in use should be evaluated for redundancy and robustness in providing egress when building damage occurs, including the issues of transfer floors, stair spacing and locations, and stairwell enclosure impact resistance.

f. Fire protection ratings and safety factors for structural transfer systems should be evaluated for their adequacy relative to the role of transfer systems in building stability.

8.2 Chapter Observations, Findings, and Recommendations

The following sections present observations, findings, and recommendations specifically made in each chapter of this report, including the discussion of building codes and fire standards in Chapter 1 and the limited metallurgical examination of steel from the WTC towers and WTC 7 in Appendix C.

8.2.1 Chapter 1: Building Codes and Fire Standards

Observations and Findings

a. The decision to include aircraft impact as a design parameter for a building would clearly result in a major change in the design, livability, usability, and cost of buildings. In addition, reliably designing a building to survive the impact of the largest aircraft available now or in the future may not be possible. These types of loads and analyses are not suitable for inclusion in minimum loads required for design of all buildings. Just as the possibility of a Boeing 707 impact was a consideration in the original design of WTC 1 and WTC 2, there may be situations where it is desirable to evaluate building survival for impact of an airplane of a specific size traveling at a specific speed. Although there is limited public information available on this topic, interested building owners and design professionals would require further guidance for application to buildings.

b. The ASTM E119 Standard Fire Test was developed as a comparative test, not a predictive one. In effect, the Standard Fire Test is used to evaluate the relative performance (fire endurance) of different construction assemblies under controlled laboratory conditions, not to predict performance in real, uncontrolled fires.

8.2.2 Chapter 2: WTC 1 and WTC 2

8.2.2.1 Observations and Findings

a. The structural damage sustained by each of the two buildings as a result of the terrorist attacks was massive. The fact that the structures were able to sustain this level of damage and remain standing for an extended period of time is remarkable and is the reason that most building occupants were able to evacuate safely. Events of this type, resulting in such substantial damage, are generally not considered in building design, and the ability of these structures to successfully withstand such damage is noteworthy.

b. Preliminary analyses of the damaged structures, together with the fact the structures remained standing for an extended period of time, suggest that, absent other severe loading events such as a windstorm or earthquake, the buildings could have remained standing in their damaged states until subjected to some significant additional load. However, the structures were subjected to a second, simultaneous severe loading event in the form of the fires caused by the aircraft impacts.

c. The large quantity of jet fuel carried by each aircraft ignited upon impact into each building. A significant portion of this fuel was consumed immediately in the ensuing fireballs. The remaining fuel is believed either to have flowed down through the buildings or to have burned off within a few minutes of the aircraft impact. The heat produced by this burning jet fuel does not by itself appear to have been sufficient to initiate the structural collapses. However, as the burning jet fuel spread across several floors of the buildings, it ignited much of the buildings' contents, causing simultaneous fires across several floors of both buildings. The heat output from these fires is estimated to have been comparable to the power produced by a large commercial power generating station. Over a period of many minutes, this heat induced additional stresses into the damaged structural frames while simultaneously softening and weakening these frames. This additional loading and the resulting damage were sufficient to induce the collapse of both structures.

d. Because the aircraft impacts into the two buildings are not believed to have been sufficient to cause collapse without the ensuing fires, the obvious question is whether the fires alone, without the damage from the aircraft impact, would have been sufficient to cause such a collapse. The capabilities of the fire protection systems make it extremely unlikely that such fires would develop without some unusual triggering event like the aircraft impact. For all other cases, the fire protection for the tower buildings provided in-depth protection. The first line of defense was the automatic sprinkler protection. The sprinkler system was intended to respond quickly and automatically to extinguish or confine a fire. The second line of defense consisted of the manual (FDNY/Port Authority Fire Brigade) firefighting capabilities, which were supported by the building standpipe system, emergency fire department use elevators, smoke control system, and other features. Manual suppression by FDNY was the principal fire protection mechanism that controlled a large fire that occurred in the buildings in 1975. Finally, the last line of defense was the structural fire resistance. The fire resistance capabilities would not be called upon unless both the automatic and manual suppression systems just described failed. In the incident of September 11, not only did the aircraft impacts disable the first two lines of defense, they also are believed to have dislodged fireproofing and imposed major additional stresses on the structural system.

e. Had some other event disabled both the automatic and manual suppression capabilities and a fire of major proportions occurred while the structural framing system and its fireproofing remained intact, the third line of defense, structural fireproofing, would have become critical. The thickness and quality of the fireproofing materials would have been key factors in the rate and extent of temperature rise in the floor trusses and other structural members. In the preparation of this report, there has not been sufficient analysis to predict the temperature and resulting change in strength of the individual structural members in order to approximate the overall response of the structure. Given the redundancy in the framing system and the capability of that system to redistribute load from a weakened member to other parts of the structural system, it is impossible, without extensive modeling and other analysis, to make a credible prediction of how the buildings would have responded to an extremely severe fire in a situation where there was no prior structural damage. Such simulations were not performed within the scope of this study, but should be performed in the future.

f. Buildings are designed to withstand loading events that are deemed credible hazards and to protect the public safety in the event such credible hazards are experienced. Buildings are not designed to withstand any event that could ever conceivably occur, and any building can collapse if subjected to a sufficiently extreme loading event. Communities adopt building codes to help building designers and regulators determine those loading events that should be considered as credible hazards in the design process. These building codes are developed by the design and regulatory communities themselves, through a voluntary committee consensus process. Prior to September 11, 2001, it was the consensus of these communities that aircraft impact was not a sufficiently credible hazard to warrant routine consideration in the design of buildings and, therefore, the building codes did not require that such events be considered in building design. Nevertheless, the design of WTC 1 and WTC 2 did include at least some consideration of the probable response of the buildings to an aircraft impact, albeit a somewhat smaller and slower moving aircraft than those actually involved in the September 11 events. Building codes do consider fire as a credible hazard and include extensive requirements to control the spread of fire throughout buildings, to delay the onset of fire-induced structural collapse, and to facilitate the safe egress of building occupants in a fire event. For fire-protected steel-frame buildings, like WTC 1 and WTC 2, these code requirements had been deemed effective and, in fact, prior to September 11, there was no record of the fire-induced-collapse of such structures, despite some very large uncontrolled fires.

g. The ability of the two towers to withstand aircraft impacts without immediate collapse was a direct function of their design and construction characteristics, as was the vulnerability of the two towers to collapse a result of the combined effects of the impacts and ensuing fires. Many buildings with other design and construction characteristics would have been more vulnerable to collapse in these events than the two towers, and few may have been less vulnerable. It was not the purpose of this study to assess the code-conformance of the building design and construction, or to judge the adequacy of these features. However, during the course of this study, the structural and fire protection features of the buildings were examined. The study did not reveal any specific structural features that would be regarded as substandard, and, in fact, many structural and fire protection features of the design and construction were found to be superior to the minimum code requirements.

h. Several building design features have been identified as key to the buildings' ability to remain standing as long as they did and to allow the evacuation of most building occupants. These included the following:

- robustness and redundancy of the steel framing system
- adequate egress stairways that were well marked and lighted
- conscientious implementation of emergency exiting training programs for building tenants

i. Similarly, several design features have been identified that may have played a role in allowing the buildings to collapse in the manner that they did and in the inability of victims at and above the impact floors to safely exit. These features should not be regarded either as design deficiencies or as features that should be prohibited in future building codes. Rather, these are features that should be subjected to more detailed evaluation, in order to understand their contribution to the performance of these buildings and how they may perform in other buildings. These include the following:

- the type of steel floor truss system present in these buildings and their structural robustness and redundancy when compared to other structural systems
- use of impact-resistant enclosures around egress paths
- resistance of passive fire protection to blasts and impacts in buildings designed to provide resistance to such hazards
- grouping emergency egress stairways in the central building core, as opposed to dispersing them throughout the structure

j. During the course of this study, the question of whether building codes should be changed in some way to make future buildings more resistant to such attacks was frequently explored. Depending on the size of the aircraft, it may not be technically feasible to develop design provisions that would enable all structures to be designed and constructed to resist the effects of impacts by rapidly moving aircraft, and the ensuing fires, without collapse. In addition, the cost of constructing such structures might be so large as to make this type of design intent practically infeasible.

Although the attacks on the World Trade Center are a reason to question design philosophies, the BPS Team believes there are insufficient data to determine whether there is a reasonable threat of attacks on specific buildings to recommend inclusion of such requirements in building codes. Some believe the likelihood of such attacks on any specific building is deemed sufficiently low to not be considered at all. However, individual building developers may wish to consider design provisions for improving redundancy and robustness for such unforeseen events, particularly for structures that, by nature of their design or occupancy, may be especially susceptible to such incidents. Although some conceptual changes to the building codes that could make buildings more resistant to fire or impact damage or more conducive to occupant egress were identified in the course of this study, the BPS Team felt that extensive technical, policy, and economic study of these concepts should be performed before any specific code change recommendations are developed. This report specifically recommends such additional studies. Future building code revisions may be considered after the technical details of the collapses and other building responses to damage are better understood.

8.2.2.2 Recommendations

The scope of this study was not intended to include in-depth analysis of many issues that should be explored before final conclusions are reached. Additional studies of the performance of WTC 1 and WTC 2 during the events of September 11, 2001, and of related building performance issues should be conducted. These include the following:

a. During the course of this study, it was not possible to determine the condition of the interior structure of the two towers, after aircraft impact and before collapse. Detailed modeling of the aircraft impacts into the buildings should be conducted in order to provide understanding of the probable damage state immediately following the impacts.

b. Preliminary studies of the growth and heat flux produced by the fires were conducted. Although these studies provided useful insight into the buildings' behavior, they were not of sufficient detail to permit an understanding of the probable distribution of temperatures in the buildings at various stages of the event and the resulting stress state of the structures as the fires progressed. Detailed modeling of the fires should be conducted and combined with structural modeling to develop specific failure modes likely to have occurred.

c. The floor framing system for the two towers was complex and substantially more redundant than typical bar joist floor systems. Detailed modeling of these floor systems and their connections should be conducted to understand the effects of localized overloads and failures to determine ultimate failure modes. Other types of common building framing should also be examined for these effects.

d. The fire-performance of steel trusses with spray-applied fire protection, and with end restraint conditions similar to those present in the two towers, is not well understood, but is likely critical to the building collapse. Studies of the fire-performance of this structural system should be conducted.

e. Observation of the debris generated by the collapse of the towers and of damaged adjacent structures suggests that spray-applied fireproofing may be vulnerable to mechanical damage from blasts and impacts. This vulnerability is not well understood. Tests of these materials should be conducted to understand how well they withstand such mechanical damage and to determine whether it is appropriate and feasible to improve their resistance to such damage.

f. In the past, tall buildings have occasionally been damaged, typically by earthquakes, and experienced collapse within the damaged zones. Those structures were able to arrest collapse before they progressed to a state of total collapse. The two WTC towers were able to arrest collapse from the impact damage, but not from the resulting fires when combined with the impact effects of the aircraft attacks. Studies should be conducted to determine, given the great size and weight of the two towers, whether there are feasible design and construction features that would permit such buildings to arrest or limit a collapse, once it began.

8.2.3 Chapter 3: WTC 3

8.2.3.1 Observations

WTC 3 was subjected to extraordinary loading from the impact and weight of debris from the two adjacent 110-story towers. It is noteworthy that the building resisted both horizontal and vertical progressive collapse when subjected to debris from WTC 2. The overloaded portions were able to break away from the rest of the structure without pulling it down, and the remaining structural system was able to remain stable and support the debris load. The structure was even capable of protecting occupants on lower floors after the collapse of WTC 1.

8.2.3.2 Recommendations

WTC 3 should be studied further to understand how it resisted progressive collapse.

8.2.4 Chapter 4: WTC 4, 5, and 6

WTC 4, 5, and 6 have similar design features, although their building configurations are somewhat different. Because WTC 5 was the only building accessible for observation, most of the following discussion focuses on this building. However, the observations, findings, and recommendations are assumed to be applicable to all three buildings.

8.2.4.1 Observations and Findings

a. All three buildings suffered extensive fire and impact damage and significant partial collapse. The condition of the stairways in WTC 5 indicates that, for the duration of this fire, the fire doors and the fire protective covering on the walls performed well. There was, however, damage to the fire side of the painted fire doors, and the damage-free condition on the inside or stairwell side of those same doors indicates the doors performed as specified for the fire condition that WTC 5 experienced. These stairway enclosures were unusual for buildings that have experienced fire because they were not impacted by water from firefighting operations. In addition, the stairway doors were not opened during the fire and remained latched and closed throughout the burnout of the floors. Therefore, general conclusions regarding the effectiveness of this type of stairway construction may not be warranted.

b. The steel generally behaved as expected given the fire conditions in WTC 5. Many beams developed catenary action as illustrated in Figure 4-14. Some columns buckled, as shown in Figure 4-17. The one exception is the limited internal structural collapse in WTC 5. The fire-induced failure that led to this collapse was unexpected. As in the rest of the building, the steel beams were expected to deflect significantly, yet carry the load. This was not the case where the beam connections failed. The failure most likely occurred during the heating of the structure because the columns remained straight and freestanding after the collapse.

c. The structural redundancy provided by the exterior wall pipe columns helped to support the cantilevered floors. This was important because it kept the cantilevers from buckling near the columns as might be expected.

d. The limited structural collapse in WTC 5 due to fire impact as described in Section 4.3.2 appeared to be caused by a combination of excessive shear loads and tensile forces acting on the simple shear connections of the infill beams. The existence of high shear loads was evident in many of the column tree beam stub cantilevers that formed diagonal tension field failure mechanisms in the cantilever webs, as seen in Figure 4-19.

e. The end bearing resistance of the beam web was less than the double shear strength of the high-strength bolts. An increased edge distance might have prevented this collapse by increasing the connections' tensile strength. The failure most likely began on the 8th floor and progressed downward, because the 9th floor did not collapse. The 4th floor and those below remained intact.

f. The 7th floor framing was shop-coated. In some locations, the paint appeared to be in good condition and not discolored by the fire. Paint usually blisters and chars when heated to temperatures of about 100 °C (212 °F). This indicates that the fire protection material remained on the steel during the early phase of the fire and may have fallen off relatively later in the fire as the beams twisted, deflected, and buckled. Additional measures for proper adhesion may be required when applying spray-on fire protection to painted steel.

g. On the lower floors, the steel beams appeared to have heat damage from direct fire impact and there was little or no evidence of shop painting, indicating that fireproofing material was either missing before the fire or delaminated early in the fire exposure.

h. In general, the buildings responded as expected to the impact loadings. Collapse was often localized, although half of WTC 4 and most of the central part of WTC 6 suffered collapse on all floors. The damage was consistent with the observed impact load.

i. Reinforced web openings in steel beams performed well, as no damage or local buckling was observed at these locations.

j. The automatic sprinkler system did not control the fires. Some sprinkler heads fused, but there was no evidence of significant water damage, due to a lack of water. This is consistent with the lack of water damage in the bookstore on the lower level and the complete burnout of the upper floors.

8.2.4.2 Recommendations

The scope of this study and the limited time allotted prevented in-depth analysis of many issues that should be explored before final conclusions are reached. Additional studies of the performance of WTC 4, 5, and 6 during the events of September 11, 2001, and related building performance issues should be conducted. These include the following:

a. There is insufficient understanding of the performance of connections and their adequacy under real fire exposures as discussed in Appendix A. This is an area that needs further study. The samples discussed in Section 4.3.2 should be useful in such a study.

b. A determination of the combined structural and fire properties of the critical structural connections should be made to permit prediction of their behavior under overload conditions. This can be accomplished with a combination of thermal transfer modeling, structural finite element modeling (FEM), and full-scale physical testing.

8.2.5 Chapter 5: WTC 7

8.2.5.1 Observations and Findings

a. This office building was built over an electrical substation and a power plant, comparable in size to that operated by a small commercial utility. It also stored a significant amount of diesel oil and had a structural system with numerous horizontal transfers for gravity and lateral loads.

b. The loss of the east penthouse on the videotape suggests that the collapse event was initiated by the loss of structural integrity in one of the transfer systems. Loss of structural integrity was likely a result of weakening caused by fires on the 5th to 7th floors. The specifics of the fires in WTC 7 and how they caused the building to collapse remain unknown at this time. Although the total diesel fuel on the premises contained massive potential energy, the best hypothesis has only a low probability of occurrence. Further research, investigation, and analyses are needed to resolve this issue.

c. The collapse of WTC 7 was different from that of WTC 1 and WTC 2. The towers showered debris in a wide radius as their external frames essentially "peeled" outward and fell from the top to the bottom. In contrast, the collapse of WTC 7 had a relatively small debris field because the façade came straight down, suggesting an internal collapse. Review of video footage indicates that the collapse began at the lower floors on the east side. Studies of WTC 7 indicate that the collapse began in the lower stories, either through failure of major load transfer members located above an electrical substation structure or in columns in the stories above the transfer structure. Loss of strength due to the transfer trusses could explain why the building imploded, with collapse initiating at an interior location. The collapse may have then spread to the west, causing interior members to continue collapsing. The building at this point may have had extensive interior structural failures that then led to the collapse of the overall building, including the cantilever transfer girders along the north elevation, the strong diaphragms at the 5th and 7th floors, and the seat connections between the interior beams and columns at the building perimeter.

8.2.5.2 Recommendations

Certain issues should be explored before final conclusions are reached and additional studies of the performance of WTC 7, and related building performance issues should be conducted. These include the following:

a. Additional data should be collected to confirm the extent of the damage to the south face of the building caused by falling debris.

b. Determination of the specific fuel loads, especially at the lower levels, is important to identify possible fuel supplied to sustain the fires for a substantial duration. Areas of interest include storage rooms, file rooms, spaces with high-density combustible materials, and locations of fuel lines. The control and operation of the emergency power system, including generators and storage tanks, needs to be thoroughly understood. Specifically, the ability of the diesel fuel pumps to continue to operate and send fuel to the upper floors after a fuel line is severed should be confirmed.

c. Modeling and analysis of the interaction between the fires and structural members are important. Specifically, the anticipated temperatures and duration of the fires and the effects of the fires on the structure need to be examined, with an emphasis on the behavior of transfer systems and their connections.

d. Suggested mechanisms for a progressive collapse should be studied and confirmed. How the collapse of an unknown number of gravity columns brought down the whole building must be explained.

e. The role of the axial capacity between the beam-column connection and the relatively strong structural diaphragms may have had in the progressive collapse should be explained.

f. The level of fire resistance and the ratio of capacity-to-demand required for structural members and connections deemed to be critical to the performance of the building should be studied. The collapse of some structural members and connections may be more detrimental to the overall performance of the building than other structural members. The adequacy of current design provisions for members whose failure could result in large-scale collapse should also be studied.

8.2.6 Chapter 6: Bankers Trust Building

8.2.6.1 Observations and Findings

a. An evaluation of the damage patterns revealed several interesting interpretations. The spandrels were sheared by the impactor, between column lines C and D, from the 23rd to the 19th floors. The D-8 column splices failed at the 18th floor and at the 16th floor, but there are no clues to indicate why column splice tension overload occurred at this location. However, unlike the spandrels above, the girder-column connections at column lines C and D failed. Although severed from the column above and below, column D-8 remained suspended from the girders spanning between column lines E and D. These girders developed large vertical and lateral deformations (twisting). The twisting and bending of these girders may have extended the zone of collapse to bays bounded by column lines C and E. If the column splices had not failed at the 16th and 18th floors, it is possible the extent of collapse may have been limited to the single bay in the path of the impactor. This enlarged zone of damage continued until the collapse was arrested on the 8th floor. It is unlikely that dynamic effects caused the damage to column D-8 below the 16th floor; otherwise, the collapse should have progressed all the way to the ground. It is possible that the column splice failures and the resulting large deformations (twisting) of the spandrels caused the remaining portion of column D-8 to lose lateral bracing, and the collapse was not arrested until the energy of the impactor and debris pile was sufficiently diminished to halt the collapse. If this actually accounted for the enlargement of the damage zone, the restraint of the twisting deformations may have prevented the failure of column D-8.

b. Although a considerable amount of debris fell from the upper floors onto the first-floor extension to the north, a two-story deep pile of debris accumulated on the 8th floor. By one estimate, although the debris distributed some of its weight by bridging action, the net effect would have been a 500-percent increase in dead load moment for the supporting beam. Based on the computed results, and in the absence of wind, it appears that the connections would have been able to support more than 500 percent of the estimated dead load moments before any hinging would occur. This may explain why multiple stories of debris came to rest at the 8th floor without incurring additional damage to the structure.

c. Because column D-8 failed below the 16th floor, the beam-to-column moment connection was the single most significant structural feature that helped limit the damage. The portion of the building above the collapsed floors was held in place by frame action of the perimeter. Static elastic analyses of the moment frame show very high stress levels; however, there was a negligible deformation directly above the damaged structure. Furthermore, connections that enable the beams to develop some membrane capacity improve a structure's ability to arrest collapse. The typical floor beam end connections with their A307 bolts were overloaded in direct tension. High-strength bolts would have provided significantly greater tensile ability and possibly held more beams in place through catenary action. Inelastic analyses demonstrate the role of the weaker connections in the response of the structure. Finally, stronger column splices may have made it more difficult for the damaged column to separate from the upper column. Heavier column splices could have allowed the damaged column to function as a hanger and limit the amount of collapsed area, or they could have tended to pull more of the frame down.

8.2.6.2 Recommendations

It is difficult to draw conclusions and more detailed study is required to understand how the collapse was halted. As better descriptions of the structural details become available, the observed patterns of damage may provide useful information in the calibration of numerical simulation tools. Some issues requiring further study are:

a. Whether the observed damage in the column flange, and not at the beam flange, of the moment frames top connection plates is due to high restraint in the welds.

b. Why the bottom flange welded connection has typically failed at the fillet weld to beam interface and not at the fillet weld to seat plate interface.

c. The impact response of various moment-connected details.

d. Whether composite construction would reduce local collapse zones. (There were no shear connectors to provide composite action between the floor beams and slab. Composite construction would have increased the capacity of the members and may have dissipated more of the impact energy; however, it may have also pulled a greater extent of the adjoining regions into the collapse zone.)

e. Whether perimeter rebar in the slabs could improve the structural response by providing catenary action and tensile force resistance in the slabs to reduce local collapse zones.

f. Whether the partial-strength connections permitted members to break away from the structure, thereby limiting the extent of damage. (If the moment connections had been designed for the capacity of the sections [as opposed to fully rigid partial strength based on design load and stiffness requirements], the building performance is likely to have been different.)

g. Whether the collapse zone would have been limited if the spandrels on the 16th, 17th, and 18th floors had not been so grossly distorted through twisting.

8.2.7 Chapter 7: Peripheral Buildings

8.2.7.1 Observations and Findings

a. Steel-frame construction from the 1900s through the 1980s, though different in many details, performed well under significant impact loads by limiting impact damages and progressive collapse to local areas.

b. Heavy unreinforced masonry façades were observed to absorb significant amounts of impact energy in the Verizon and 90 West Street buildings. Heavy masonry façades like those in the Verizon, 90 West Street, or even 130 Cedar Street buildings may also provide an alternative load path for a damaged structure.

c. Older, early-century fireproofing methods of concrete-, brick-, and terra cotta tile-encased steel frames performed well, even after 90+ years, and protected the 90 West Street building from extensive structural damage.

8.2.7.2 Recommendations

The known data and conditions of the perimeter structures after the impact damage should be utilized as a basis for calibration, comparison, and verification of existing software intended to predict such behavior, and for the development of new software for the prediction of the ability of structures to sustain localized and global overload conditions.

8.2.8 Appendix C: Limited Metallurgical Examination

Two structural steel samples from the WTC site were observed to have unusual erosion patterns. One sample is believed to be from WTC 7 and the other from either WTC 1 or WTC 2.

8.2.8.1 Observations and Findings

a. The thinning of the steel occurred by high temperature corrosion due to a combination of oxidation and sulfidation.

b. Heating of the steel into a hot corrosive environment approaching 1,000 °C (1,800 °F) results in the formation of a eutectic mixture of iron, oxygen, and sulfur that liquefied the steel.

c. The sulfidation attack of steel grain boundaries accelerated the corrosion and erosion of the steel.

d. The high concentration of sulfides in the grain boundaries of the corroded regions of the steel occurred due to copper diffusing from the high-strength low-alloy (HSLA) steel combining with iron and sulfur, making both discrete and continuous sulfides in the steel grain boundaries.

8.2.8.2 Recommendations

The severe corrosion and subsequent erosion of Samples 1 and 2 constitute an unusual event. No clear explanation for the source of the sulfur has been identified. The rate of corrosion is also unknown. It is possible that this was the result of long-term heating in the ground following the collapse of the buildings. It is also possible that the phenomenon started prior to collapse and accelerated the weakening of the steel structure. A detailed study into the mechanisms of this phenomenon is needed to determine what risk, if any, is presented to existing steel structures exposed to severe and long-burning fires.

8.3 Building Performance Study Recommendations for Future Study

The BPS Team has developed recommendations for specific issues, based on the study of the performance of the WTC towers and surrounding buildings in response to the impact and fire damage that occurred. These recommendations have a broader scope than the important issue of building concepts and design for mitigating damage from terrorist attacks, and also address the level at which resources should be expended for aircraft security, how the fire protection and structural engineering communities should increase their interaction in building design and construction, possible considerations for improved egress in damaged structures, the public understanding of typical building design capacities, issues related to the study process and future activities, and issues for communities to consider when they are developing emergency response plans that include engineering response.

8.3.1 National Response

Resources should be directed primarily to aviation and other security measures rather than to hardening buildings against airplane impact. The relationship and cooperation between public and private organizations should be evaluated to determine the most effective mechanisms and approaches in the response of the nation to such disasters.

8.3.2 Interaction of Structural Elements and Fire

The existing prescriptive fire resistance rating method (ASTM E119) does not provide sufficient information to determine how long a building component in a structural system can be expected to perform in an actual fire. A method of assessing performance of structural members and connections as part of a structural system in building fires is needed for designers and emergency personnel.

The behavior of the structural system under fire conditions should be considered as an integral part of the structural design. Recommendations are to:

- Develop design tools, including an integrated model that predicts heating conditions produced by the fire, temperature rise of the structural component, and structural response.
- Provide interdisciplinary training in structures and fire protection for both structural engineers and fire protection engineers.

Performance criteria and test methods for fireproofing materials relative to their durability, adhesion, and cohesion when exposed to abrasion, shock, vibration, rapid temperature rise, and high-temperature exposures need further study.

8.3.3 Interaction of Professions in Design

The structural, fire protection, mechanical, architectural, blast, explosion, earthquake, and wind engineering communities need to work together to develop guidance for vulnerability assessment, retrofit, and the design of concrete and steel structures to mitigate or reduce the probability of progressive collapse under single- and multiple-hazard scenarios.

An improved level of interaction between structural and fire protection engineers is encouraged. Recommendations are to:

- Consider behavior of the structural system under fire as an integral part of the design process.
- Provide cross-training of fire protection and structural engineers in the performance of structures and building fires.

8.3.4 Fire Protection Engineering Discipline

The continued development of a system for performance-based design is encouraged. Recommendations are to:

- Improve the existing models that simulate fire and spread in structures, as well as the impact of fire and smoke on structures and people.
- Improve the database on material burning behavior.

8.3.5 Building Evacuation

The following topics were not explicitly examined during this study, but are recognized as important aspects of designing buildings for impact and fire events. Recommendations for further study are to:

- Perform an analysis of occupant behavior during evacuation of the buildings at WTC to improve the design of fire alarm and egress systems in high-rise buildings.
- Perform an analysis of the design basis of evacuation systems in high-rise buildings to assess the adequacy of the current design practice, which relies on phased evacuation.
- Evaluate the use of elevators as part of the means of egress for mobility-impaired people as well as the general building population for the evacuation of high-rise buildings. In addition, the use of elevators for access by emergency personnel needs to be evaluated.

8.3.6 Emergency Personnel

One of the most serious dangers firefighters and other emergency responders face is partial or total collapse of buildings. Recommended steps to provide better protection to emergency personnel are to:

- Have fire protection and structural engineers assist emergency personnel in developing pre-plans for buildings and structures to include more detailed assessments of hazards and response of structural elements and performance of buildings during fires, including identification of critical structural elements.
- Develop training materials and courses for emergency personnel with regard to the effects of fire on steel.
- Review collaboration efforts between the emergency personnel and engineering professions so that engineers may assist emergency personnel in assessments during an incident.

8.3.7 Education of Stakeholders

Stakeholders (e.g., owners, operators, tenants, authorities, designers) should be further educated about building codes, the minimum design loads typically addressed for building design, and the extreme events that are not addressed by building codes. Should stakeholders desire to address events not included in the building codes, they should understand the process of developing and implementing strategies to mitigate damage from extreme events.

Stakeholders should also be educated about the expected performance of their building when renovations, or changes in use or occupancy, occur and the building is subjected to different floor or fire loads. For instance, if the occupancy in a building changes to one with a higher fire hazard, stakeholders should have the fire protection systems reviewed to ensure there is adequate fire protection. Or, if the structural load is increased with a new occupancy, the structural support system should be reviewed to ensure it can carry the new load.

8.3.8 Study Process

This report benefited from a tremendous amount of professional volunteerism in response to this unprecedented national disaster. Improvements can be made that would aid the process for any future efforts. Recommendations are to:

- Provide resources that are proportional to the required level of effort.
- Provide better access to data, including building information, interviews, samples, site photos, and documentation.

8.3.9 Archival Information

Archival information has been collected and provides the groundwork for continued study. It is recommended that a coordinated effort for the preservation of this and other relevant information be undertaken by a responsible organization or agency, capable of maintaining and managing such information, This effort would include:

- cataloging all photographic data collected to date
- enhancing video data collected for both quality and timeline
- conducting interviews with building occupants, witnesses, rescue workers, and any others who may provide valuable information
- initiating public requests for information

8.3.10 SEAoNY Structural Engineering Emergency Response Plan

As with any first-time event, difficulties were encountered at the beginning of the relationship between the volunteer engineering community and the local government agencies. Lessons learned in hindsight can be valuable to other engineering and professional organizations throughout the country. Appendix F presents recommendations that can be used as a basis for the development of other, similar plans.

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A Overview of Fire Protection in Buildings

A.1. Introduction

This appendix presents background information on the fire and life safety aspects of buildings for the interested reader. This review of fire behavior outlines burning characteristics of materials as well as the effect of building characteristics on the temperatures experienced. The description of the effect of fire exposure on steel and concrete structural members is intended to improve understanding of how these structural members respond when heated and also what measures are commonly used to limit temperature rise in structural members. Finally, a brief discussion on evacuation behavior in high-rise buildings is included to provide some context to the comments made in the report concerning the design of the means of egress and the evacuation process in WTC 1 and WTC 2.

A.2 Fire Behavior

Important aspects of fire behavior in the affected buildings involves the following issues:

- burning behavior of materials, including mass loss and energy release rates
- stages of fire development
- behavior of fully developed fires, including the role of ventilation, temperature development, and duration

A.2.1 Burning Behavior of Materials

Once a material is ignited, a fire spreads across the fuel object until it becomes fully involved. The spread at which flame travels over the surface of the material is dependent on the fuel composition, orientation, surface to mass ratio, incident heat, and air supply. Given sufficient air, the energy released from a fire is dictated by the incident heat on the fuel and the fuel characteristics, most notably the heat of combustion and latent heat of vaporization. The relationship of these parameters to the energy release rate is given by:

$$\dot{Q}'' = \frac{\dot{q}''}{L_v}\Delta H_c \qquad \text{(A-1)}$$

where:

$\dot{Q}''$ = energy release rate per unit surface area of fuel

$\dot{q}''$ = incident heat per unit surface area of fuel (i.e., heat flux)

L_v = latent heat of vaporization

ΔH_c = heat of combustion

The effective heat of combustion for a mixture of wood and plastics is on the order of 16 kJ/g. For fully developed fires, the radiant heat flux is approximately 150 to 200 kW/m^2. The latent heat of vaporization for a range of wood and plastics is 5 to 8 kJ/g. Thus, the mass burning rate per unit surface area in typical office building fires ranges from 20 to 40 g/m^2-s and the associated energy release rate per unit surface area ranges from 320 to 640 kW/m^2.

In typical fires, as the fire grows in size, the energy release rate increases to a peak value as depicted in Figure A-1. The increase in the heat release rate with time depends on the fuel characteristics, incident heat, and available air supply. Sample curves for alternate materials, described in the fire protection literature as "slow," "medium," and "fast" growth rate fires, are illustrated in Figure A-2.

At some point, the heat release rate of the fire will become limited by either the amount of fuel or the amount of oxygen that is available; this is referred to as the peak heat release rate. Peak heat release rate data can be obtained through experimental testing and is available for many types of materials and fuels. Table A.1 includes a list of selected common items and their associated peak heat release rates.

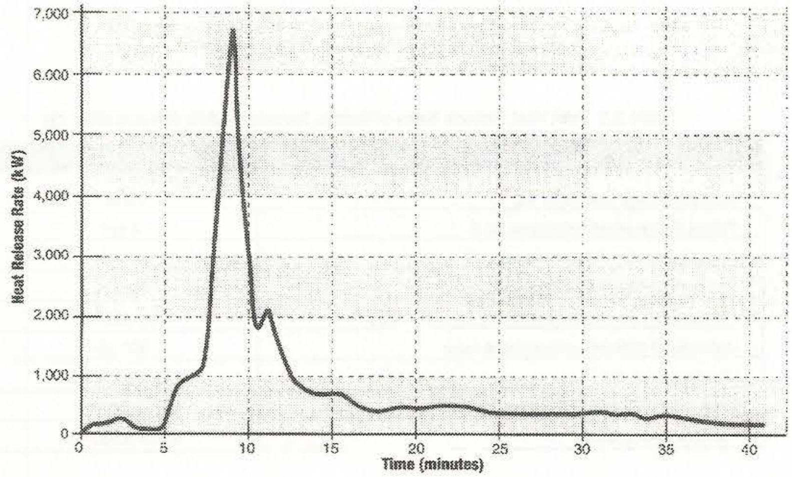


Figure A-1 Heat release rate for office module (Madrzykowski 1996).

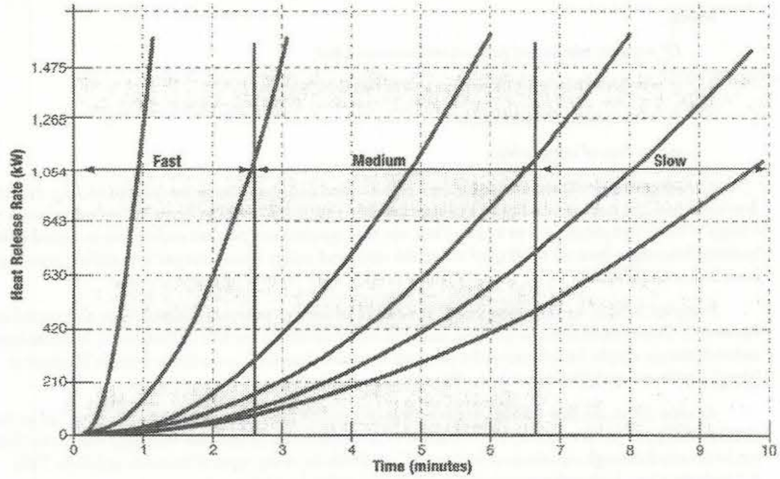


Figure A-2 Fire growth rates (from SFPE Handbook of Fire Protection Engineering).

Table A.1 Peak Heat Release Rates of Various Materials (NFPA 92B and NFPA 72)

Item	Heat Release Rate
Crumpled brown lunch bag, 6 g	1.2 kW
Folded double-sheet newspaper, 22 g	4 kW
Crumpled double sheet newspaper, 22 g	17 kW
Medium wastebasket with milk cartons	100 kW
Plastic trash bag with cellulosic material (1.2–14 kg)	120–350 kW
Upholstered chair with polyurethane foam	350 kW
Christmas tree, dry	500-650 kW
Latex foam mattress (heat at room door)	1,200 kW
Furnished living room	4,000–8,000 kW

After a fire has reached its peak heat release rate, it will decline after some period of time. At this point, most of the available fuel has typically been burned and the fire will slowly decrease in size. The length of the decay phase depends on what type of fuel is available, how complete was the combustion of the fuel, how much oxygen is present in the compartment, and whether any type of suppression is occurring. The burning rate of liquid fuels is on the order of 50 g/m^2-s, with an associated energy release rate per unit surface area of approximately 2,000 kW/m^2. The burning rate per unit area of information is useful to estimate the duration of a fire involving a particular fuel spread over a specified area.

A.2.2 Stages of Fire Development

Generally, fires are initiated within a single fuel object. The smoke produced from the burning object is transported by a smoke plume and collects in the upper portion of the space as a layer. The smoke plume also transports the heat produced by the fire into the smoke layer, causing the smoke layer to increase in depth and also temperature. This smoke layer radiates energy back to unburned fuels in the space, causing them to increase in temperature.

Fire spreads to other objects either by radiation from the flames attached to the originally burning item or from the smoke layer. As other objects ignite, the temperature of the smoke layer increases further, radiating more heat to other objects. In small compartments, the unburned objects may ignite nearly simultaneously. This situation is referred to as "flashover." In large compartments, it is more likely that objects will ignite sequentially. The sequence of the ignitions depends on the fuel arrangement, and composition and ventilation available to support combustion of available fuels.

A.2.3 Behavior of Fully Developed Fires

A fully-developed fire is one that reaches a steady state burning stage, where the mass loss rate is relatively constant during that period. The equilibrium situation may occur as a result of a limited ventilation supply (in ventilation controlled fires) or due to characteristics of the fuel (fuel-controlled fires).

If the rate of mass burning based on the incident heat flux and fuel characteristics (see Section A.2.1) exceeds the amount that can be supported by the available air supply, the burning becomes ventilation controlled. Otherwise, the fire is referred to as being fuel controlled. The ventilation air for the fires may be supplied from openings to the room, such as open windows or doors, or other sources such as HVAC systems.

Given that the heat released per unit of oxygen is a relatively constant value of 13.1 kJ/g for common fuels, the air supply required to support fires of a particular heat release rate can be determined. For every 1 MW of heat release rate, 76 g/s of oxygen is consumed. Considering that air is 21 percent oxygen, this flow of oxygen requires a flow of 0.24 m^3/s (500 cfm) of ambient air. In the case of WTC 1 and WTC 2, for a 3-GW fire, a flow of 1,500,000 cfm of air was required to support that fire. That airflow would have been supplied via openings in the exterior wall and the shaft walls.

Most of the research on fully-developed fires has been conducted in relatively small spaces with near-square floor plans. In such cases, the conditions (temperature of the smoke and incident heat on the enclosure) are relatively uniform throughout the upper portion of the space. However, Thomas and Bennetts (1999) have documented differences in that behavior for ventilation controlled fires in long, thin spaces or in large areas. In such cases, the burning occurs in the fuel nearest to the supply source of air. Temperatures are observed to be greatest nearest to the supply source of air.

In large or complex buildings, the incident flux on the structural elements is expected to vary over the entire space of fire involvement. A range of developing numerical models have the ability to compute the variation of the fire imposed heat flux on a 3-dimensional grid. The Fire Dynamics Simulator from the National Institute of Standards and Technology (NIST) is an example of such a model that has the promise of developing into a tool that could be used to estimate the variation in incident heat flux on structural elements over a large space of fire involvement.

A.3 Structural Response to Fire

A.3.1 Effect of Fire on Steel

A.3.1.1 Introduction

Fire resistance is defined as the property of a building assembly to withstand fire, or give protection from it (ASTM 2001a). Included in the definition of fire resistance are two issues. The first issue is the ability of a building assembly to maintain its structural integrity and stability despite exposure to fire. Secondly, for some assemblies such as walls and floor-ceiling assemblies, fire resistance also involves serving as a barrier to fire spread.

Fire resistance is commonly assessed by subjecting a prototype assembly to a standard test. Results from the test are reported in terms of a fire resistance rating, in units of hours, based on the time duration of the test that the building assembly continues to satisfy the acceptance criteria in the test.

Fire resistance rating requirements for different building components are specified in building codes. These ratings depend on the type of occupancy, number of stories, and floor area. Because the standard test is intended to be a comparative test and is not intended to predict actual performance, the hourly fire resistance ratings acquired in the tests should not be misconstrued to indicate a specific duration that a building assembly will withstand collapse in an actual fire.

Generally, the fire resistance rating of a structural member is a function of:

- applied structural load intensity,
- member type (e.g., column, beam, wall),
- member dimensions and boundary end conditions,
- incident heat flux from the fire on the member or assembly,
- type of construction material (e.g., concrete, steel, wood), and
- effect of temperature rise within the structural member on the relevant properties of the member.

The fire performance of a structural member depends on the thermal and mechanical properties of the materials of which the building component is composed. As a result of the increase in temperature caused by the fire exposure, the strength of steel decreases along with its ability to resist deformation, represented by the modulus of elasticity. In addition, deformations and other property changes occur in the materials under prolonged exposures. Likewise, concrete is affected by exposure to fire and loses strength and stiffness with increasing temperature. In addition, concrete may spall, resulting in a loss of concrete material in the assembly. Spalling is most likely in rapid-growth fires, such as may have occurred in WTC 1 and WTC 2.

The performance of fire-exposed structural members can be predicted by structural mechanics analysis methods, comparable to those applied in ambient temperature design, except that the induced deformations and property changes need to be taken into consideration.

Beams and trusses may react differently to severe fire exposures, depending on the end conditions and fabrication. Unconnected members may collapse when the stresses from applied loads exceed the available strength for beams and trusses. In the case of connected members, significant deflections may occur as a result of reduced elastic modulus, but structural integrity is preserved as a result of catenary action.

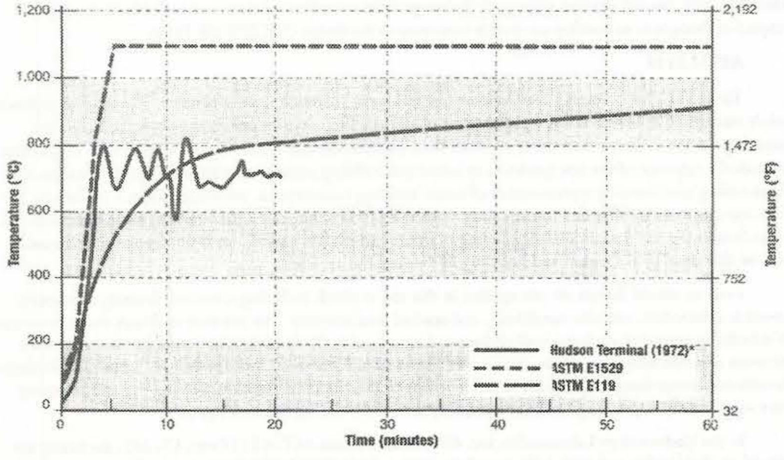
In the case of slender columns, the susceptibility for buckling increases with a decrease in the modulus of elasticity. Where connections of floor framing to columns fail, either at the ends or intermediate locations, column slenderness is increased, thereby increasing the susceptibility of a column to buckling.

Steels most often used in building design and construction are either hot-rolled or cold-drawn. Their strength depends mainly on their carbon content, though some structural steels derive a portion of their strength from a process of heat treatment known as quenching and tempering (e.g., ASTM A913 for rolled shapes and ASTM A325 and A490 for bolts).

A.3.1.2 Evaluating Fire Resistance

Performance Criteria

Building code requirements for structural fire protection are based on laboratory tests conducted in accordance with ASTM E119, Standard Test Methods for Fire Tests of Building Construction and Materials (2000). In these tests, building assemblies, such as floor-ceilings, columns, and walls are exposed to heating conditions created in a furnace, following a specified time-temperature curve. In Figure A-3, time-



*Hudson Terminal experiment conducted with normal office fuel load (6 psf) (DeCicco, et al. 1972)

Figure A-3 Comparison of exposure temperatures in standard tests.

temperature curves are presented for the standard fire exposure specified in ASTM E119, the standard hydrocarbon exposure in ASTM E1529, and a real building fire. As can be seen, each is somewhat different.

There are three performance criteria in the standard ASTM E119 test method. These are related to loadbearing capacity, insulation, and integrity:

1. **Loadbearing capacity:** For loadbearing assemblies, the test specimen shall not collapse in such a way that it no longer performs the loadbearing function for which it was constructed.
2. **Insulation:** For assemblies such as floors-ceilings and walls that have the function of separating two parts of a building,
   a. the average temperature rise at the unexposed face of the specimen shall not exceed 139 °C (282 °F), and
   b. the maximum temperature rise at the unexposed face of the specimen shall not exceed 181 °C (358 °F).
3. **Integrity:** For assemblies such as walls, floors, and roofs, the formation of openings through which flames or hot gases can pass shall not occur. Loss of integrity is deemed to have occurred when a specified cotton wool pad applied to the unexposed face is ignited.

Tests are conducted on prototype designs. The fire-resistance rating applies to replicates of the tested assembly, with limited changes permitted. Rules, guidelines, and correlations are available to assess the impact of changes or to develop acceptable variations to the design (ASCE/SFPE 1999).

ASTM E119

The ASTM E119 test is a comparative test and is not intended to be predictive. The test fire exposure, while recognized as severe, is not representative of all fires. Heat transfer conditions associated with the exposing fire are different than those in actual fires. Further, the test is not a full-scale test, with no attempt to scale the response of the test specimen to actual size building assemblies. Although the test requires that floor-ceiling specimens be representative of actual building construction, achieving this in a 14-foot by 17-foot test specimen is difficult. Consequently, ASTM E119 is principally a thermal test, not a structural test, even though the test floor is loaded. Loading of floors and roofs is done to see if the fireproofing material will be dislodged by deflection and buckling of the steel during a fire.

Further, several factors are not applied in this test method, including structural framing continuity, member interaction, restraint conditions, and applied load intensity. The test only evaluates the performance of a building assembly, such as a wall or floor-ceiling assembly. The test does not consider the interaction between adjacent assemblies or the behavior of the structural frame. In "real" buildings, beam/girder/column connections range from simple shear to full moment connections and framing member size and geometry vary significantly, depending on the structural system and building size and layout.

In the Underwriters Laboratories, Inc. (UL) version of the ASTM E119 test, UL 263, the beams are placed on shelf angles and steel wedges are driven by sledgehammers between the end of the beam and the heavy massive steel and concrete furnace frame. This is referred to as a "restrained beam," and the fire test results are published in Volume 1 of the UL Fire Resistance Directory, which is the major reference used by architects and engineers to select designs that meet the building code requirements for fire resistance ratings. The UL Fire Resistance Directory also publishes unrestrained fire resistance ratings based on critical temperature rise in the steel member as discussed in Section A.3.1.6. In spite of the ASTM E119 test limitations relative to the structural conditions that exist in real buildings, the fire test is conservative to the point that more fire protection material is required than has been demonstrated necessary in large scale fire tests conducted and reported in the international fire research literature.

There has been much interest in revising the ASTM E119 Standard Fire Test. Arguments are posed that the fire exposure is too severe, while others suggest that the fire exposure is not severe enough. A good compromise is a performance oriented analysis using design fire curves for very specific occupancies and building geometry while still permitting the use of ASTM E119 for general applications.

For most of the 1900s, there was a single U.S. standard time-temperature curve described by ASTM E119. Most of the world adopted that curve or one similar in running the test furnaces.

In 1928, Ingberg of the National Bureau of Standards published a paper on the severity of fire (Ingberg 1928) in which he equated the gross combustible fuel load (combustible content in mass per unit area) to the potential fire exposure in terms of duration of exposure to a fire following the standard (ASTM E119) fire curve. Although subsequent research has shown the simple relationship proposed by Ingberg holds only in limited cases where the fire ventilation is the same as that present in his test series, his equation is still widely published in texts and used as the basis of regulation.

In the 1950s and 1960s, it was demonstrated that, for severe, fully involved fires, the intensity and duration of burning within compartments and other enclosures were also functions of the availability of air for combustion, commonly referred to as ventilation and normally coming from openings such as doors and broken windows or from forced ventilation from the HVAC system.

In Sweden, an extensive family of fire curves has been developed, by test, for fully involved (i.e., post flashover) fires as a combined function of fuel load and ventilation (Magnusson and Thelandersson 1970). The published curves have peak temperatures of 600–1,100 °C (1,100–2,000 °F).

Most recently, Ian Thomas in Australia has demonstrated with reduced scale models that the combustion process in facilities where there is a depth from the vent opening (e.g., broken windows) to the actual fuel can produce conditions where a large portion of the vaporized fuel actually burns at a point removed from the location of the solid fuel (combustible material) source. Thomas' experiments used fully involved spaces where the depth from the vent opening was at least twice the width of the test space. In these experiments, the air supply drawn into the test space by the fire was insufficient to burn all of the available fuel. Fuel once vaporized was transported to the openings and burned there, producing an unexpectedly high heat flux on the elements at and near the vent opening. The importance of Thomas' work is that it demonstrates the fact that, in many fires, the reality is that the fire exposing the structural elements is not necessarily a constant in either time or space.

Fortunately, there are now advanced numerical models capable of describing the fire caused environment in detail.

ASTM E1529 and UL 1709: The Hydrocarbon Pool Curves

In the late 1980s, as a result of failures of fireproofed steel members exposed to petroleum spill fires, the petroleum industry felt a need to develop a new test curve. The curve developed was designed to apply a sudden and intense shock, typified by a large hydrocarbon pool fire either burning in the open or in some other situation where there was no significant restraint to the flow of combustion air to the burning pool fire. ASTM E1529 was developed to answer this need. The objective of this ASTM test is to almost instantaneously impose 158 kW/m^2 (50,000 Btu/ft^2-hr) on the element under test. Additionally a similar but somewhat more severe test procedure has been developed by Underwriters Laboratories and published as their standard UL 1709. The UL test is designed to impose 200 kW/m^2 (65,000 Btu/ft^2-hr) on the test element. This unusual difference in the ASTM and UL standards reflects a technical difference of opinion between the two organizations. The tests are often quoted as a time-temperature curve quickly reaching and maintaining a test furnace temperature of 1,093 °C (2,000 °F) in the case of the ASTM standard and 1,143 °C (2,089 °F) at UL. The hydrocarbon time-temperature curve is, however, actually a test-specific item and can vary some from test apparatus to test apparatus.

The ASTM E119 curve was derived from experiments and is empirically based; however, ASTM E1529 exposure is based on judgment, experience, and a database of experiments concerning the measurement of the temperatures involved in large hydrocarbon fires. The incident flux approximates the incident flux on a member completely bathed in the flame from a large free-burning pool fire. Although both of the ASTM curves are useful in conducting tests of fireproofed building elements as pre-installment tests, they are not predictions of the intensity of actual fires and are often not appropriate as an input to models or other computations seeking to assess a fire hazard for a building.

A prime impact of the high flux "shock" exposure is to test the capability of the fireproofing to survive such exposure. In addition, such thermal shock could induce spalling in concrete systems.

Comparison between ASTM E119, ASTM E1529, and UL 1709 is further complicated by instrumentation differences in the two "hydrocarbon fire" tests and that used in the ASTM E119 test. In particular, different thermocouple installations are used to control and record furnace temperatures in the respective tests. In the ASTM E119 test, the thermocouples are contained within a protective capped steel pipe, resulting in a time delay between the actual and recorded furnace temperatures. In the hydrocarbon tests, the thermocouples are bare, thereby providing a more timely indication of the actual gas temperature. The lag in ASTM E119 is most pronounced at the start of the test. Figure A-3 provides a plot of the two standard curves with an additional curve of the approximate actual temperature (if measured with bare thermocouples) in an ASTM E119 furnace test. Most of the tests to date have been conducted using the UL 1709 curve. Many tested items show a significantly shorter time to failure using the UL 1709 procedure as compared to the ASTM E119 procedure.

A.3.1.3 Response of High-rise, Steel-frame Buildings in Previous Fire Incidents

In recent years, three notable fires have occurred in steel frame buildings, though none involved the total floor area as in WTC 1 and WTC 2. However, prior to September 11, 2001, no protected steel frame buildings had been known to collapse due to fire. These previous three fire incidents include the following:

- 1st Interstate Bank Building, Los Angeles, May 4-5, 1988
- Broadgate Phase 8, UK, 1990
- One Meridian Plaza, Philadelphia, February 23-24, 1991

The steel in the 1st Interstate Bank Building and One Meridian Plaza was protected with spray-applied protection. Because the fire occurred at the Broadgate complex while it was under construction, the steel beams had not yet been protected. The fire durations of the three incidents are indicated in Table A.2. The durations noted in the table refer to the overall duration of the incident. The fire duration in a particular area of the building was likely less than that noted.

In the case of the fire at One Meridian Plaza, the fire burned uncontrolled for the first 11 hours and lasted 19 hours. Contents from nine floors were completely consumed in the fire. In addition to these experiences in fire incidents, as a result of the Broadgate fire, British Steel and the Building Research Establishment performed a series of six experiments at Cordington in the mid-1990s to investigate the behavior of steel frame buildings. These experiments were conducted in a simulated, eight-story building. Secondary steel beams were not protected. Despite the temperature of the steel beam reaching 800–900 °C

Table A.2 Fire Duration in Previous Fire Incidents in Steel-frame Buildings

Building	Date	Fire Duration (hours)
1st Interstate Bank Building	May 4-5, 1988	3.5
Broadgate Phase 8	1990	4.5
One Meridian Plaza	February 23-24, 1991	19 (11 uncontrolled)

(1,500–1,700 °F) in three tests (well above the traditionally assumed critical temperature of 600 °C [1,100 °F]), no collapse was observed in any of the six experiments.

One important aspect of these previous incidents is that the columns remained intact and sustained their load carrying ability throughout the fire incidents (though there was no structural damage caused by impacts). Throughout the fire in One Meridian Plaza, horizontal forces were exerted on the columns by the girders and despite the 24- to 36-inch deflections of the girders, floor beams, and concrete and steel deck floor slabs, the columns continued to stabilize the building throughout the fire and for several years after the fire.

Questions have been raised about the comparison of the structural performance of the WTC 1 and WTC 2 and the Empire State Building. In the case of the Empire State Building:

1. The impacting aircraft was a U. S. Army Air Force B-25 bomber weighing 12 tons with a fuel capacity of 975 gallons, which, at the time of the crash, was traveling at a speed estimated to be 250 mph;
2. Crash damage to structural steel was confined to three steel beams. One exterior wall column withstood the direct impact without visible effect;
3. Exterior walls are ornamental cast aluminum panels under windows with steel trim backed by 8 inches of brick. The walls at columns are 8 inches of limestone backed by 8 inches of brick supported on steel framing; and
4. The floors above the Saturday morning plane crash were largely vacant and unoccupied, so the fire load was minimal and perhaps close to zero. Fire was confined to a portion of two floors. Because the building had few occupants at the time of the crash, the fire department could concentrate on controlling and extinguishing the fire.

A.3.1.4 Properties of Steel

The principal thermal properties that influence the temperature rise and distribution in a member are its thermal conductivity, specific heat, and density. The temperature-dependence of the thermal conductivity and specific heat for steel are depicted in Figure A-4.

The mechanical properties that affect the fire performance of structural members are strength, modulus of elasticity, coefficient of thermal expansion, and creep of the component materials at elevated temperatures. Information on the thermal and mechanical properties at elevated temperatures for various types of steel is available in the literature (Lie 1992, Milke 1995, Kodur and Harmathy 2002).

References to the tensile or compressive strength of steel relate either to the yield strength or ultimate strength. Figure A-5 shows the stress-strain curves for a structural steel (ASTM A36) at room temperature and elevated temperatures. As indicated in the figure, the yield and ultimate strength decrease with temperature as does the modulus of elasticity. Figure A-6 shows the variation of strength with temperature

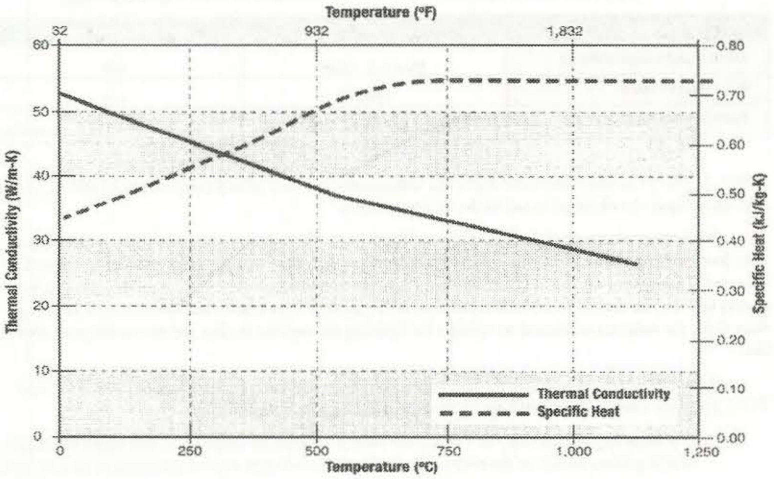


Figure A-4 Thermal properties of steel at elevated temperatures (SFPE 2000).

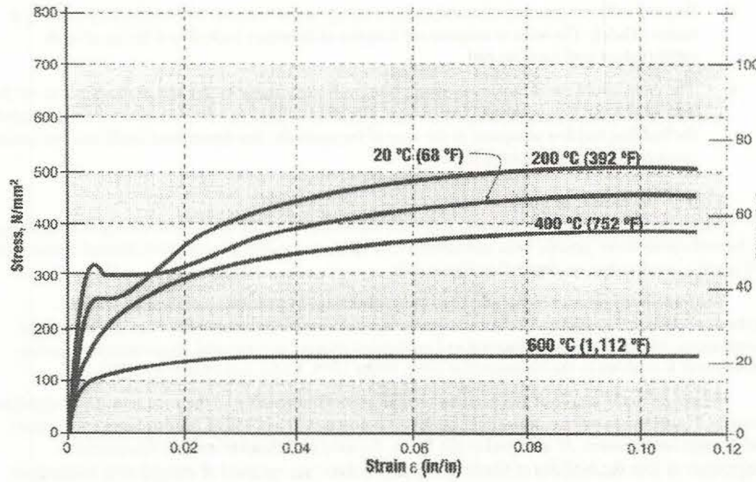


Figure A-5 Stress-strain curves for structural steel (ASTM A36) at a range of temperatures (SFPE 2000).

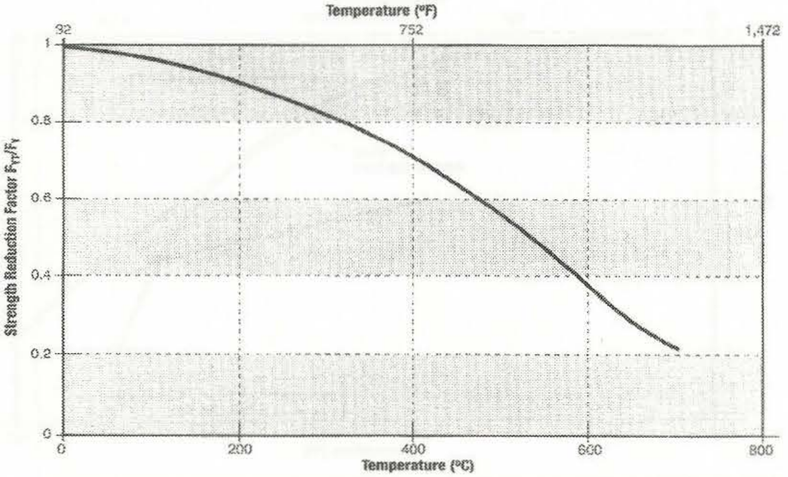


Figure A-6 Strength of steel at elevated temperatures (Lie 1992).

(ratio of strength at elevated temperature to that at room temperature) for hot rolled steel such as A36. As indicated in the figure, if the steel attains a temperature of 550 °C (1,022 °F), the remaining strength is approximately half of the value at ambient temperature.

The modulus of elasticity, E_0, is about 210×10^3 MPa for a variety of common steels at room temperature. The variation of the modulus of elasticity with temperature for structural steels and steel reinforcing bars is presented in Figure A-7. As in the case of strength, if the steel attains a temperature of 550 °C (1,022 °F), the modulus of elasticity is reduced to approximately half of the value at ambient temperature.

Figure A-8 shows the variation of yield strength of light gauge steel at elevated temperatures, corresponding to 0.5 percent, 1.5 percent, and 2 percent strains based on the relationships in Gerlich (1995), Makelainen and Miller (1983), and BSI (2000).

In addition to the changes in the properties with increasing temperature, steel expands with increasing temperature. The coefficient of thermal expansion for structural steel is approximately 11×10^{-6} mm/mm-°C. Consequently, an unrestrained, 20-meter-long steel member that experiences a temperature increase of 500 °C (1,022 °F) will expand approximately 110 mm. WTC 5 had many buckled girders and beams on the burned-out fire floors where the expansion was restrained.

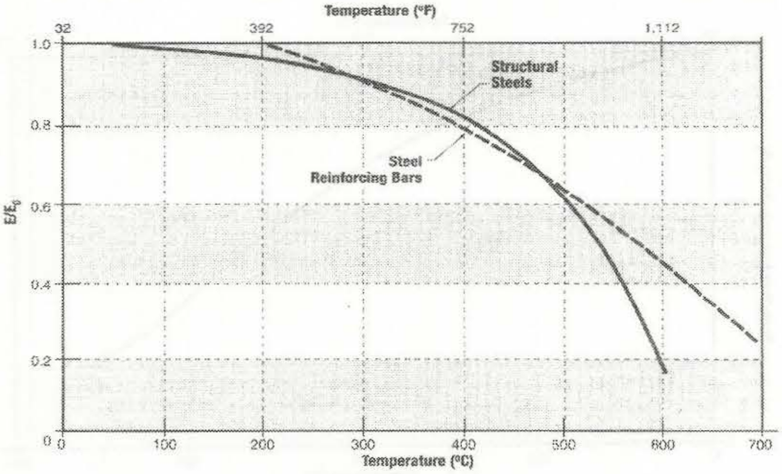


Figure A-7 Modulus of elasticity at elevated temperatures for structural steels and steel reinforcing bars (SFPE 2000).

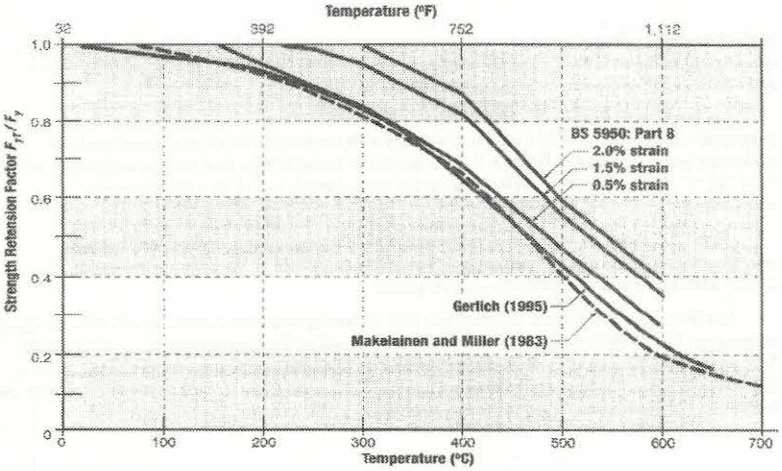


Figure A-8 Reduction of the yield strength of cold-formed light-gauge steel at elevated temperatures.

An approximate melting point for steel is 1,400 °C (2,500 °F); however, the melting temperature for a particular steel component varies with the steel alloy used.

A.3.1.5 Fire Protection Techniques for Steel

Given the significant reduction in the mechanical properties of steel at temperatures on the order of 540 °C (1,000 °F), isolated and unprotected steel members subjected to the standard test heating environment are only able to maintain their structural integrity for 10 to 20 minutes, depending on the mass and size of the structural member. Unprotected open web steel joists supporting concrete floors in the ASTM E119 fire test have been tested and collapse in 7 minutes (Wang and Kodur 2000).

Isolated and unprotected steel box columns 8 inches x 6 1/2 inches formed using 1/4-inch plate and channels in an ASTM E119 fire test collapse in about 14 minutes (Kodur and Lie 1995). Consequently, measures are taken to protect loadbearing, steel structural members where the members are part of fire resistant assemblies. A variety of methods are available to limit the temperature rise of steel structural members, including the insulation method and the capacitive method.

Insulation Method: The insulation method consists of attaching insulating spray-applied materials, board materials, or blankets to the external surface of the steel member. A variety of insulating materials have been used following this method of protection, including mineral-fiber or cementitious spray-applied materials, gypsum wallboard, asbestos, intumescent coatings, Portland cement concrete, Portland cement plaster, ceramic tiles, and masonry materials. The insulation may be sprayed directly onto the member being protected, such as is commonly done for steel columns, beams, or open web steel joists. The spray-applied mineral fiber, fire resistive coating is a factory mixed product consisting of manufactured inorganic fibers, proprietary cement-type binders, and other additives in low concentrations to promote wetting, set, and dust control. Air setting, hydraulic setting, and ceramic setting binders can be used in varying quantities and combinations or singly, depending on the particular application.

Alternatively, the insulation may be used to form a "membrane" around the structural member, in which case a fire resistive barrier is placed between a potential fire source and the steel member. An example of membrane protection is a suspended ceiling positioned below open web steel joists. (In order for a suspended ceiling assembly to perform effectively as a membrane form of protection, it must remain in place despite the fire exposure. Only some suspended ceiling assemblies have this capability.)

In most of the WTC complex buildings and tall buildings built over the last 50 years, the preferred method has been spray-applied mineral fiber or cementitious materials. Of these 50 years, for the first 20 years the product contained asbestos and for the last 30 years it has been asbestos free. The WTC 1, 2, and 7 incidents are the first known collapses of fire resisting steel frame buildings protected with this type of fireproofing material. Occasionally, a portion of the steel is protected with a spray or trowel applied plaster or Portland cement (e.g., Gunite or shotcrete).

Capacitive Method: The capacitive heat sink method is based on the principle of using the heat capacity of a protective material to absorb heat. In this case, the supplementing material absorbs the heat as it enters the steel and acts as a heat sink. Common examples include concrete filled hollow steel columns and water filled hollow steel columns (Kodur and Lie 1995). In addition, a concrete floor slab may act as a heat sink to reduce the temperature of a supporting beam or open web steel joist.

A.3.1.6 Temperature Rise in Steel

In building materials such as steel, a critical temperature is often referenced at which the integrity of fully-loaded structural members becomes questionable. The critical temperature for steel members varies with the type of steel structural member (e.g., beams, columns, bar joists, or reinforcing steel). North

American Test Standards (e.g., ASTM E119) assume a critical temperature of 538 °C (1,000 °F) for structural steel columns. The critical temperatures for columns and other steel structural elements are given in Table A.3. The critical temperature is defined as approximately the temperature where the steel has lost approximately 50 percent of its yield strength from that at room temperature. In an actual structure, the actual impact of such heating of the steel will also depend on the actual imposed load, member end restraint (axial and rotational), and other factors as discussed in Section A.3.1.7.

Table A.3 Critical Temperatures for Various Types of Steel

Steel	Temperature
Columns	538 °C (1,000 °F)
Beams	593 °C (1,100 °F)
Open Web Steel Joists	593 °C (1,100 °F)
Reinforcing Steel	593 °C (1,100 °F)
Prestressing Steel	426 °C (800 °F)

To limit the loss of strength and stiffness, external fire protection is provided to the steel structural members to satisfy required fire resistance ratings. This is usually achieved by fire protecting the steel members to keep the temperature of the steel, in case of a fire, from reaching a critical limit. Traditionally, the amount of fire protection needed is based on the results of standard fire resistance tests.

The temperature attained in a fire-exposed steel member depends on the fire exposure, characteristics of the protection provided, and the size and mass of the steel. For steel members protected with direct-applied insulating materials, the role of the insulating materials is strongly dependent on their thermal conductivity and thickness.

The role of the fire exposure and size and mass of the steel can be demonstrated by analyzing the temperature rise in two protected steel columns with two different fire exposures. For this comparative analysis, the fire exposure associated with two standard fire resistance tests is selected, ASTM E119 and UL 1709. The following two column sizes are selected for this comparative analysis:

- W14X193
- steel box column, 36 inches x 16 inches, with a wall thickness of 7/8 inch for the 36-inch-wide side and 15/16 inch for the 16-inch-wide side

In the first analysis, the steel columns are considered to be unprotected. The results of the analysis are presented in Figure A-9. In the second analysis, 1 inch of a spray-applied, mineral fiber insulation material was assumed to be present (the thermal conductivity of the insulation material was assumed to be 0.116 W/m-K). The results of this analysis are presented in Figure A-10.

In both analyses, the resulting steel column temperatures follow expected trends. The more massive column (the tube) experiences less temperature rise for the same fire exposure than the lighter column (the W14x193). The unprotected columns reach critical temperatures exposed to ASTM E119 condition in 15 to 18 minutes. For the more severe UL 1709 exposure, the unprotected columns reach critical temperatures in 6 to 7 minutes. In contrast, the temperature of the protected columns after 2 hours of exposure to the ASTM E119 conditions is 240 °C (464 °F) for the tube, while the temperature of the W14x193 is 330 °C (626 °F). For the more severe fire exposure associated with UL 1709, the temperature of the steel columns after 2 hours is 60–80 °C (140–176 °F) greater than for each of the steel columns exposed to the ASTM E119 conditions.

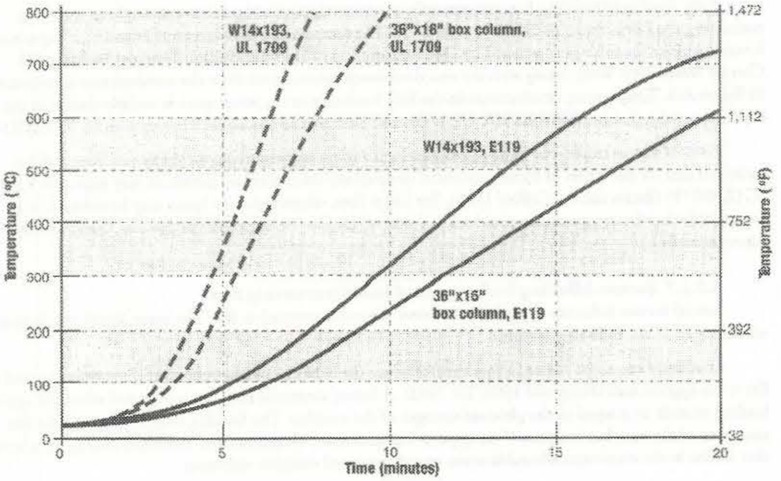


Figure A-9 Steel temperature rise due to fire exposure for unprotected steel column.

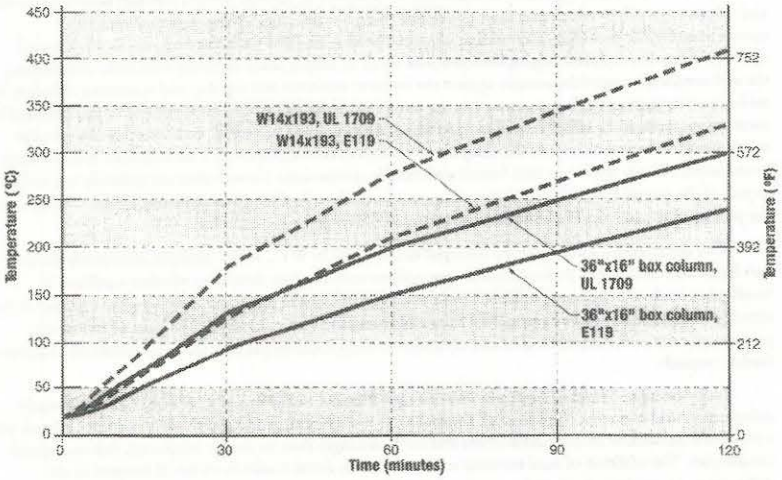


Figure A-10 Steel temperature rise due to fire exposure for steel column protected with 1 inch of spray-applied fireproofing.

Fully developed building fires can generally attain average gas temperatures throughout the room containing the fire in excess of 1,000 °C (1,800 °F). The temperature measurements acquired in experiments involving office furnishings conducted by DeCicco, et al. (1972) in the Hudson Terminal Building (30 Church Street, New York), along with the two time-temperature curves from the standard tests is presented in Figure A-3. Temperature development in the first 5 minutes in the room space is notably similar in the experiment with that in ASTM E1529, UL 1709, and the bare thermocouple temperatures for ASTM E119.

Greater temperatures may be acquired locally in a room and especially within flames. Research has indicated that, in the center of flames generated by relatively small fires, temperatures may approach 1,300 °C (2,400 °F) (Baum and McCaffrey 1988). For larger fires, where radiation losses may be reduced, it is conceivable that fire temperatures could reach 1,400 °C (2,550 °F), although this has not been confirmed experimentally.

A.3.1.7 Factors Affecting Performance of Steel Structures in Fire

Several factors influence the behavior of steel structures exposed to fire. The more significant factors are discussed in the following sections.

Loading: One of the major factors that influence the behavior of a structural steel member exposed to fire is the applied load (Fitzgerald 1998, Lie 1992). A loss of structural integrity is expected when the applied loading exceeds or is equal to the ultimate strength of the member. The limiting temperature and the fire resistance of the member increases if the applied load decreases. Traditional fire resistance tests apply a load that results in the maximum allowable stress on the structural member resistance.

Connections: Beam-to-column connections in modern steel-framed buildings may be either of bolted or welded construction, or a combination of these types. Most are designed to transmit shears from the beam to the column, although some connections are designed to provide flexural restraint between the beam and column, as well, in which case they are termed "moment resisting." When moment-resisting connections are not provided in a building, diagonal bracing or shear walls must be provided for lateral stability. When fire-induced sagging deformations occur in simple beam elements with shear connections, the end connections provide restraint against the induced rotations and develop end moments, reducing the mid-span moments in the beams, as well as the tensile catenary action. The moment and tension resisted by connections reduces the effective load ratio to which the beams are subjected, thereby enhancing the fire resistance of the beams as long as the integrity of the connection is preserved. This beneficial effect is more pronounced in large multi-bay steel frames with simple connections. Connections are generally not included as part of the assembly tested in traditional fire resistance tests. Further, most modeling efforts assume that the pre-fire characteristics of a connection are preserved during the fire exposure.

The investigating team observed damaged connections in WTC 5. For example, distorted bolts and bolt holes were found. The performance of connections seem to often determine whether a collapse is localized or leads to progressive collapse. In the standard fire tests of structural members, the member to be tested is wedged into a massive restraining frame. No connections are involved. The issue of connection performance under fire exposure is critical to understanding building performance and should be a subject of further research.

End Restraint: The structural response of a steel member under fire conditions can be significantly enhanced by end restraints (Gewain and Troup 2001). For the same loading and fire conditions, a beam with a rotational restraint at its ends deflects less and survives longer than its simply supported, free-to-expand counterpart. The addition of axial restraint to the end of the beam results in an initial increase in the deflections, due to the lack of axial expansion relief. With further heating, however, the rate of increase in deflection slows.

Effectiveness of Fireproofing: The acceptability of a particular fireproofing material as an insulator is examined as part of ASTM E119. The fireproofing material should form a stable thickness of insulating cover for the steel. Mechanical or impact damage to the fireproofing material prior to the fire exposure that results in a loss of insulating material reduces the ability of the material to act as an insulator (Ryder, et al. 2002). During the fire exposure in the ASTM E119 tests, fireproofing material may fall off as a result of thermal strains caused by differing amounts of expansion in the fireproofing and steel, excess curvature of the steel, or decomposition of the fireproofing material. If the fall-off occurs early in the test or fire exposure, the performance of the assembly is likely to be unsatisfactory. However, if the fireproofing material falls off late in the test or at the time when the fire is declining in intensity, the impact of the lost protection may not be significant. Several test methods other than ASTM E119 can be followed to assess the performance characteristics of fireproofing material. These tests are indicated in Table A.4.

Both the sprayed fiber and, to a lesser extent, cementitious materials, can sometimes fail to adhere to the steel, be mechanically damaged, or otherwise be degraded when exposed to a fire. The current quality control testing of adhesion/cohesion and density, while helpful, does not solve the problem of assuring that the fireproofing will be present at the time of a fire and function throughout the duration of the fire exposure. Other factors that can affect the durability and performance of fireproofing include resistance to abrasion, shock, vibration, and high temperatures.

Sprinklers: Sprinkler systems can be very effective in protecting all structures from the effects of fire. Automatic sprinkler systems are considered to be an effective and economical way to apply water promptly to control or suppress a fire. In the event of fire in a building, the temperature rise in the structural members located in the vicinity of sprinklers is limited. Therefore, the fire resistance of such members is enhanced. The sprinkler piping is sized considering all sprinklers in a design area of operation that are discharging water. For office buildings, typical areas of operation are approximately 1,500 to 2,500 square feet. Should a fire involve an area larger than the area of operation, the water supply may be overwhelmed, thereby negatively impacting the effectiveness of the sprinkler system.

Table A.4 Test Methods for Spray-applied Fireproofing Materials

Standard	Title
ASTM E605	*Thickness and Density of Sprayed Fire-Resistive Materials Applied to Structural Members.*
ASTM E736	*Cohesion/Adhesion of Sprayed Fire-Resistive Materials Applied to Structural Members*
ASTM E759	*Effect of Deflection of Sprayed Fire-Resistive Materials Applied to Structural Members*
ASTM E760	*Effect of Impact on the Bonding of Sprayed Fire-Resistive Materials Applied to Structural Members*
ASTM E761	*Compressive Strength of Sprayed Fire-Resistive Materials Applied to Structural Members*
ASTM E859	*Air Erosion of Sprayed Fire-Resistive Materials Applied to Structural Members*
ASTM E937	*Corrosion of Steel by Sprayed Fire-Resistive Materials Applied to Structural Members*

Structural Interaction: In contrast to an isolated member exposed to fire, the way in which a complete structural building frame performs during a fire is influenced by the interaction of the connected structural members in both the exposed and unexposed portions of the building. This is beneficial to the overall behavior of the complete frame, because the collapse of some of the structural members may not necessarily endanger the structural stability of the overall building. In such cases, the remaining interacting members develop an alternative load path to bridge over the area of collapse. This is a current area of research and is not addressed by traditional fire resistance tests.

Tensile Membrane Action: A tensile membrane (catenary) action can be developed by metal deck and reinforced concrete floor slabs in a steel-framed building whose members are designed and built to act compositely with the concrete slab (Nwosu and Kodur 1999). This action occurs when the applied load on the slab is taken by the steel reinforcement, due to cracking of the entire depth of concrete cross-section or heating of supporting steel members beyond the critical temperature. Tensile membrane action enhances the fire resistance of a complete framed building by providing an alternative load path for structural members that have lost their loadbearing capacity.

Temperature Distribution: Depending on the protective insulation and general arrangements of members in a structure, steel members will be subjected to temperature distributions that vary along the length or over the cross-section. Members subjected to temperature variation across their sections may perform better in fire than those with uniform temperature. This is due to the fact that sections with uniform temperatures will attain their load capacity at the same time. However, in members subjected to non-uniform temperature distribution, a thermally induced curvature will occur to add to the deflections due to applied loads and some parts will attain the load limit before the others. Temperature distributions within structural members may be attained if the member is part of a wall or floor-ceiling assembly where the fire exposure is applied only to one side.

A.3.2 Effect of Fire on Concrete

A.3.2.1 General

Concrete is one of the principal materials widely used in construction and, in fire protection engineering terminology, is generally classified as Group L (loadbearing) building material: materials capable of carrying high stresses. The word concrete covers a large number of different materials, with the single common feature that they are formed by the hydration of cement. Because the hydrated cement paste amounts to only 24 to 43 volume percent of the materials present, the properties of concrete may vary widely with the aggregates used.

Traditionally, the compressive strength of concrete used to be around 20-50 MPa, which is referred to as normal-strength concrete . Depending on the density, concretes are usually subdivided into two major groups: (1) normal-weight concrete, made with normal-weight aggregate, with densities in the 2,200 to 2,400 kg/m^3 range, and (2) lightweight concrete, made with lightweight aggregate, with densities between 1,300 and 1,900 kg/m^3.

The floor slabs at WTC 1 and WTC 2 (as well as in most of the WTC buildings and vicinity) were made of concrete made of metal deck. The floor construction typically consisted of 4 inches of lightweight concrete fill on corrugated metal deck. Hence, the discussion here is focused on lightweight concrete.

A.3.2.2 Properties of Lightweight Concrete

As with steel, concrete loses strength with temperature, though some concretes maintain their ambient temperature strength up to a greater temperature than structural steel. Some lightweight concretes may not exhibit the same level of performance as normal weight concretes under severe fire conditions. In these concretes, spalling under fire conditions is one of the major concerns. The fire resistance of lightweight concrete structural members is dependent on spalling characteristics in addition to thermal and mechanical properties of lightweight concrete at elevated temperatures.

A great deal of information is available in the literature on the properties of lightweight concrete (Abrams 1979, ACI 1989, Lie 1992, Kodur and Harmathy 2002). The modulus of elasticity (E) of various concretes at room temperature may fall within a very wide range, 5.0×10^3 to 50.0×10^3 MPa, dependent mainly on the water-cement ratio in the mixture, the age of concrete, and the amount and nature of the aggregates. The modulus of elasticity decreases rapidly with the rise of temperature, and the fractional decline does not depend significantly on the type of aggregate (Kodur 2000)(see Figure A-11; E_0 in the figure is the modulus of elasticity at room temperature).

The compressive strength (σ_u) of lightweight concrete can vary within a wide range and is influenced by the same factors as the modulus of elasticity. For conventionally produced lightweight concrete (at the time of the WTC construction in 1970s), the strength at room temperature usually was in the 20 to 40 MPa range. The variation of the compressive strength with temperature is presented in Figure A-12 for two lightweight aggregate concretes, one of which is made with the addition of natural sand (Kodur 2000); $(\sigma_u)_0$ in the figures refers to the compressive strengths of concrete at room temperature). The strength decrease is minimal up to about 300 °C (570 °F); above these temperatures, the strength loss is significant.

Generally, lightweight concrete has a lower thermal conductivity, lower specific heat, and lower thermal expansion at elevated temperatures than normal-strength concrete. As an illustration, the usual ranges of variation of the specific heat for normal-weight and lightweight concretes are shown in Figure A-13.

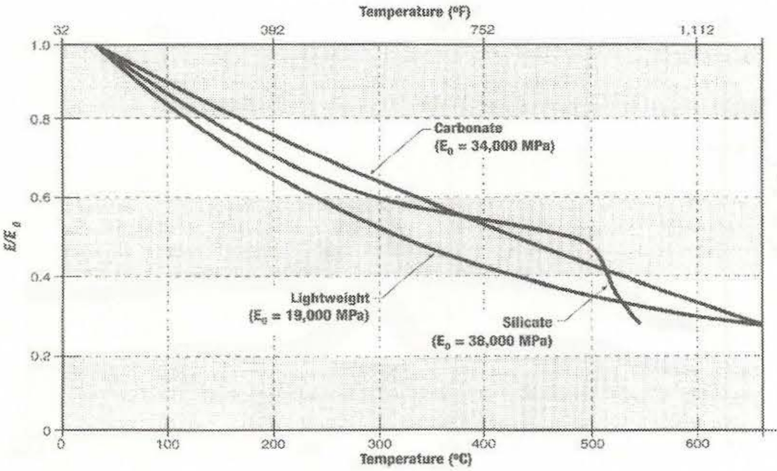


Figure A-11 The effect of temperature on the modulus of elasticity strength of different types of concretes (Kodur and Harmathy 2002).

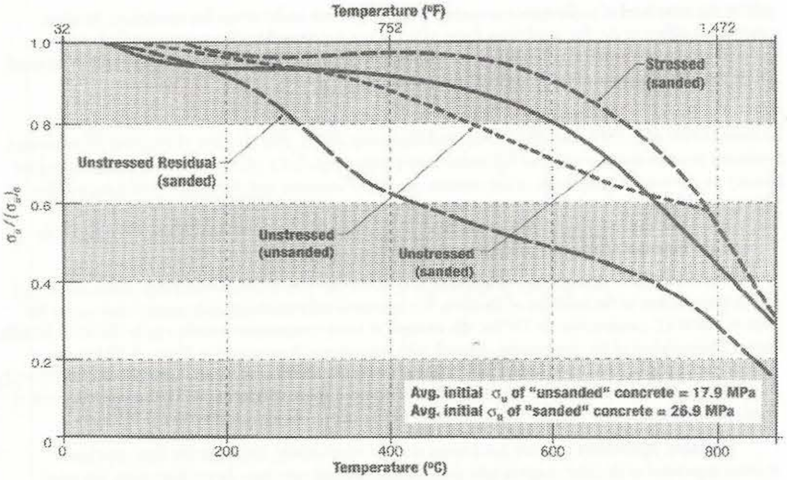


Figure A-12 Reduction of the compressive strength of two lightweight concretes (one with natural sand) at elevated temperatures (Kodur and Harmathy 2002).

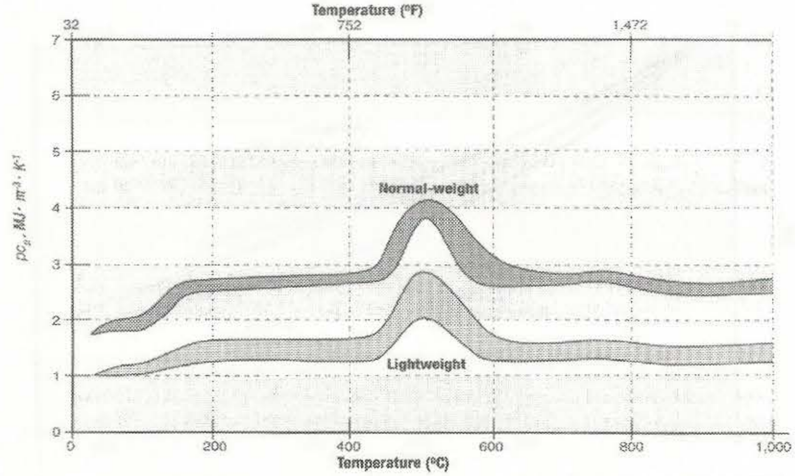


Figure A-13 Usual ranges of variation for the volume-specific heat of normal-weight and lightweight concretes (Kodur and Harmathy 2002).

Spalling is defined as the breaking of layers (pieces) of concrete from the surface of the concrete elements when it is exposed to high and rapidly rising temperatures. The spalling can occur soon after exposure to heat and can be accompanied by violent explosions, or it may happen when concrete has become so weak after heating that, when cracking develops, pieces fall off the surface. The consequences may be limited as long as the extent of the damage is small, but extensive spalling may lead to early loss of stability and integrity due to exposed reinforcement and penetration of partitions.

The extent of spalling is influenced by fire intensity, load intensity, strength and porosity of concrete mix, density, aggregate type, and internal moisture content of the concrete. Significant spalling can occur if the concrete has high moisture content and is exposed to a rapid growth fire.

A.3.3 Fire and Structural Modeling

Fire protection provided in accordance with building codes is based on laboratory tests that have no correlation with actual fires. Through the use of numerical models, the fire protection design of structural members can be determined given the exposure conditions from selected fire scenarios.

Building code requirements for fire resistance design are currently based on the presumed duration of a standard fire as a direct function of fire load, building occupancy, height, and area. The severity of actual fires is determined by additional factors, which are not now considered in current building codes except as an alternate material method or equivalency when accepted by the enforcing official. Recent fire research provides a basis for designing fire protection for structural members by analytical methods and is becoming more acceptable to the building code community. In recent years, the use of numerical methods to calculate the fire resistance of various structural members has begun to gain acceptance. These calculation methods are reliable and cost-effective and can be applied to analyze performance in a specific situation (Milke 1999). The Eurocodes currently describe a calculation method for assessing the performance of steel members exposed to actual fires. There are three analyses that need to be conducted in a numerical assessment of fire resistance:

- model fire development
- model thermal response of assemblies
- model structural response of assemblies

Fire development is modeled to describe the heating exposure provided by the fire. Next, the thermal response analysis consists of predicting the temperature rise of structural members. Finally, an analysis of structural performance can be conducted to determine the structural integrity or load carrying capacity of the fire-exposed structural members. Such an analysis needs to account for thermally-induced deformations and property changes.

The analysis of the WTC buildings and the evaluation of other existing and future tall buildings could involve both fire and structural modeling. Both mathematical and scale modeling, along with validation tests, may be needed. In terms of the numerical modeling, it is currently possible to assemble a model package that reasonably predicts the impact of the fire on strength, elongation, spalling, and other properties related to the structural stability of the buildings involved. Currently, the available models for air movement (to the fire), fire growth and the resulting environmental condition in the space, breaking of windows, heat transfer through materials (e.g., fireproofing), and temperature rise in structural elements operate independently of each other and generally do not share data. In the future, combined fire-structural models may emerge that can interactively feed the output from heat transfer analysis models to structural analysis routines on a time basis as the simulated fire progresses, with return feed to the fire models of any changes (pertinent to the fire model) that the structural computations predict, such as changes in ventilation characteristics. The combined fire-structural model(s) would permit extending the analysis of the impact of this incident to other scenarios, such as fire alone or other combinations of multiple simultaneous impacts (e.g., fire with wind, earthquake) on buildings.

Although the current models are based on sound physics, the state of the art of existing models involves uncertainties. Most of the models needed to supply the structural designer with case-specific data on temperatures of the exposed structural elements in unit area increments matching the finite elements selected for structural analysis exist. However, most of these models are as yet only partially validated.

A.4 Life Safety

The matter of high-rise evacuation has become preeminent in fire and building discussions since September 11, 2001, as a result of the fatalities of over 3,000 building occupants and emergency personnel. Life safety is provided to building occupants by either giving them the opportunity to evacuate or be protected in place. Basic life safety principles include notification, evacuation (including relocation to other floors), and protection in place (SFPE 2000).

Notification: Occupants need to be notified promptly of an emergency. In addition, communication systems should be provided that allow automatic messages to be transmitted to occupants to given them specific instructions on how to respond. These messages may also be delivered over public address systems by building safety managers or fire suppression personnel.

Evacuation: This aspect involves providing people with the means to exit the building. The egress system involves the following considerations:

- Capacity - A sufficient number of exits of adequate width to accommodate the building population need to be provided to allow occupants to evacuate safely.
- Access - Occupants need to be also to access an exit from wherever the fire is, and in sufficient time prior to the onset of untenable conditions. Alternative exits should be remotely located so that all exits are not simultaneously blocked by a single incident.
- Protected Escape Route - Exits need to be protected by fire-rated construction to limit the potential for fire and heat to impact these routes until the last occupant can reach a place of safety. In addition, such routes may also be smoke protected to limit smoke migration into the route.

In general, the means of egress system is designed so that occupants travel from the office space along access paths such as corridors or aisles until they reach the exit. An exit is commonly defined as a protected path of travel to the exit discharge (NFPA 101 2000). The stairways in a high-rise building commonly meet the definition of an exit. In general, the exit is intended to provide a continuous, unobstructed path to the exterior or to another area that is considered safe. Most codes require that exits discharge directly to the outside. Some codes, such as NFPA 101, permit up to half of the exits to discharge within the building, given that certain provisions are met.

Design considerations for high-rise buildings relative to these two options involve several aspects, including design of means of egress, the structure, and active fire protection systems, such as detection and alarm, suppression, and smoke management.

There is no universally accepted standard on emergency evacuation. Many local jurisdictions through their fire department public education programs have developed comprehensive and successful evacuation planning models, but unless locally adopted, there is no legal mandate to exercise the plans. Among the cities that have developed comprehensive programs are Seattle, Phoenix, Houston, and Portland, Oregon.

Protect in Place: The protect in place strategy is commonly employed in high-rise buildings. Occupants either remain in an area enclosed in fire rated construction or move to such a location. This approach is especially important for mobility impaired individuals. Building construction and fire protection systems are employed to protect occupants from fire and smoke spread for the duration of the incident or until rescued.

In some cases, occupants may be moved from one location to a location of relative safety while they await rescue. The Americans with Disabilities Act (ADA) of 1990 (42 USC 12181), in its design guidelines for new construction since 1993, requires that each floor in a building without a supervised sprinkler system must contain an "area of rescue assistance" (i.e., an area with direct access to an exit stairway where people unable to use stairs may await assistance during an emergency evacuation). In existing buildings, the ADA makes no reference to occupant evacuation other than to prohibit unnecessary physical barriers to mobility.

Additional information about courses and publications on emergency evacuation can be obtained at http://www.usfa.fema.gov.

A.4.1 Evacuation Process

Two methods are followed for the evacuation of buildings. One method consists of evacuating all occupants simultaneously. Alternatively, occupants may be evacuated in phases, where the floor levels closest to the fire are evacuated first, then other floor levels are evacuated on an as needed basis. Phased evacuation is instituted to permit people on the floor levels closest to the fire (i.e., those with the greatest hazard) to enter the stairway unobstructed by queues formed by people from all other floors also being in the stairway. Those who are below the emergency usually are encouraged to stay in place until the endangered people from above are already below this respective floor level. Generally, phased evacuation is followed in tall buildings, such as WTC 1 and WTC 2.

A.4.2 Analysis

A fairly simplistic model can be applied to develop a first order approximation of the time required to evacuate a high-rise building. The model is described by Nelson and MacLennan in the SFPE Handbook of Fire Protection Engineering. The following calculations are based on several major assumptions:

- All persons start to evacuate at the same time and hence no pre-movement time is considered (e. g., talking to coworkers, turning off computers, putting on coats).
- Occupant travel is not interrupted to make decisions or communicate with other individuals involved.
- The persons involved are free of any disabilities that would significantly impede their ability to keep up with the movement of the group. This includes any temporary disabilities as a result of fatigue.
- Firefighters coming into the stairway do not impose a significant impact on the flow rate of occupants traveling down the stairs.
- The controlling feature of the flow rate of people from the building is the door at the bottom of the exit stairway. This assumes that people develop a queue in the stairway that ends at the doorway at the base of the stairway. Also, the time for the first people to form the queue is assumed to be much less than the total evacuation time.
- The density of the people traveling through the doorway is in the range of observed values (i.e., 6-10 ft^2/person). As such, the flow rate per foot of effective width for each doorway would be anticipated to be in the range of 18 to 24 persons/min (see Figure A-14). Consequently, the flow rate from each doorway in the World Trade Center buildings would have been on the order of 30 to 50 persons/min.

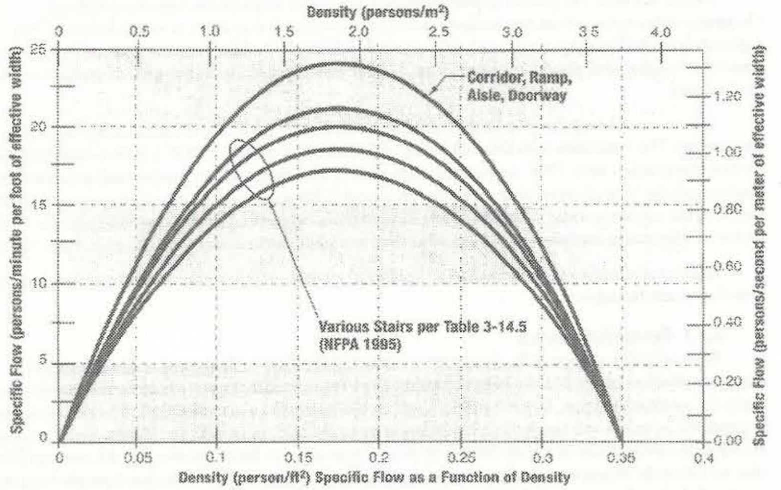


Figure A-14 Specific flow rate as a function of density (SFPE Handbook of Fire Protection Engineering).

Given these assumptions, the results presented in Figure A-15 relate to a lower limit of the time expected to evacuate the WTC towers. There were three exit stairways serving most floors of the WTC towers. Below the impact area, all stairways appeared to be available. The number of people in each building on the morning of September 11, 2001, is not known. Therefore, a range of occupant loads is included in Figure A-15.

By all indications, it was instantly apparent to the building occupants that evacuation was necessary, so very little time was likely to have transpired in pre-movement activities. The time for the leading edge of the [illegible] to descend from the lowest occupied floor [illegible] to the discharge doors on floors 1 and 2 is estimated to have taken about 3 minutes until the steady human flow reached its capacity. The sense of urgency in the evacuees is estimated to have maintained the egress flow at or near the theoretical maximum for stair exit flow (i.e., 24 persons/minute per foot).

The two end stairs were 44 inches wide and the center stair was 56 inches wide. Each stair had a single 36-inch-wide exit door at its discharge level. As such, the effective width for each stair door was 24 inches (2 feet). The expected steady flow rate from the stair doorways was 48 persons/minute. Based on an available egress time of 90 minutes in WTC 1 and 50 minutes in WTC 2, the number of persons who could have exited through the stairs is estimated to be up to13,000 for WTC 1 and up to 7,200 for WTC 2. These estimates do not include any persons who used elevators, were on the 2nd (Plaza) level or lower in the buildings at the time, or initiated evacuation in WTC 2 immediately after the impact of WTC 1.

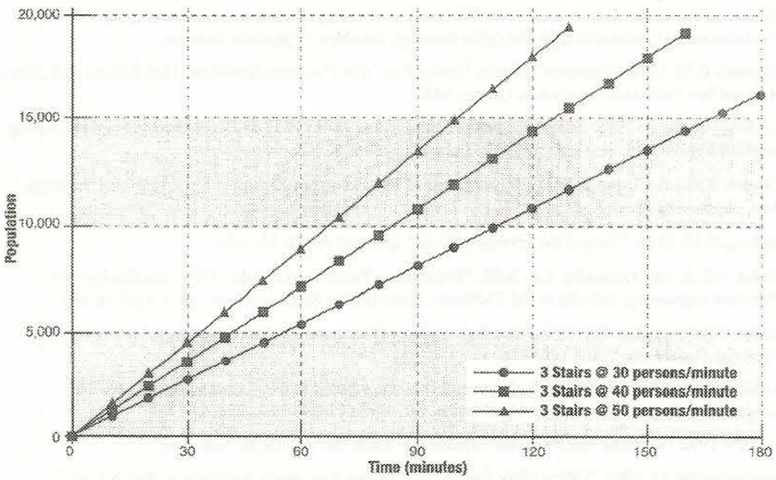


Figure A-15 Estimated evacuation times for high-rise buildings.

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Nestor Iwankiw

B Structural Steel and Steel Connections

B.1 Structural Steel

This appendix focuses mainly on the structural steel and connections in the WTC towers (WTC 1 and WTC 2), but column-tree connections in WTC 5 are also considered. Other WTC structures were fabricated from ASTM A36 and A572 grade steels, and their structural framing and connections are discussed in prior chapters.

The structural steel used in the exterior 14-inch by 14-inch columns that were spaced at 3 feet 4 inches on center around the entire periphery of each of the WTC towers was fabricated from various grades of high-strength steel with minimum specified yield stress between 36 kips per square inch (ksi) and 100 ksi (PATH-NYNJ 1976). Column plate thickness varied from 1/4 inch to 5/8 inch in the impact zone of WTC 1 for floors 89-101, and from 1/4 inch to 13/16 inch in the impact zone of WTC 2 for floors 77-87. Spandrel beams at each floor level were fabricated of matching steel and integrated into the columns as the columns and spandrel sections were prefabricated into trees. These trees were three columns wide and one to three stories high. The cross-sectional shape of the columns can be seen in Figure B-1. These varied in length from 12 feet 6 inches to 38 feet, depending on the plate thickness and location.

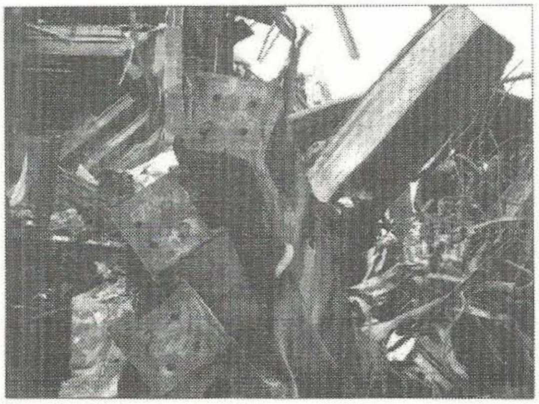


Figure B-1 Exterior column and plates.

The three columns in a panel were generally fabricated from the same grade of steel. The yield stress varied from 50 ksi to 100 ksi in increments of 5 ksi up to 90 ksi. Although most of the time the same grade of steel was used in all three columns, sometimes a column was fabricated from different grades. The difference was up to 15 ksi (i.e., 75 ksi, 85 ksi, and 90 ksi). The core columns were box sections fabricated from A36 steel plate and were 36 inches x 14–16 inches with plate thickness from 3/4 inch to 4 inches. Above floor 84, rolled or welded built-up I-shaped sections were used.

The floor system was supported by 29-inch-deep open-web joist trusses with A36 steel chord angles and steel rod diagonals. Composite 1-1/2-inch, 22-gauge metal floor deck ran parallel to double trusses that were spaced at 6 feet 8 inches. The floor deck was also supported by alternate intermediate support angles and transverse bridging trusses that were spaced at 3 feet 4 inches. The bridging truss also framed into some periphery columns. Figure 2-2 (in Chapter 2) shows the layout of a typical floor. Because 13-foot-wide and 20-foot-wide modular floor units were prefabricated for construction, the outside two trusses shared a common top chord seat connection with adjacent panels. All double trusses were attached to every other periphery column by a seat angle connection and a gusset plate that was welded to the spandrel and top chord. Therefore, all truss supports had two trusses attached to the seat connection. A single bolt was used for each truss sharing a seat connection. The bottom chord of each pair of trusses was attached to the spandrel with visco-elastic dampers that had a slip capacity of 5 kips. At the core, the trusses were connected to girders that were attached to the box or H-shaped core columns by beam seats welded to the column faces.

B.2 Mechanical Properties

Nearly all of the steel plate was produced in Japan to ASTM standards or their equivalent. None of the mill test reports were available that describe the mechanical properties and chemical composition of the steel used in the WTC structures. Approximately 100 potentially helpful steel pieces were identified at the four salvage yards that had contracts to obtain and process the WTC steel debris. These pieces have been removed and transported to the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland, for storage and further study. No coupons were taken or tested to check material conformance with specification of any plate, rolled section, bolt, weld, reinforcing steel, or concrete. Visual examination of the debris did not identify any apparent deficiencies in the structural materials and connectors.

In lieu of actual WTC steel properties, typical stress-strain curves characteristic of 3 of the 12 steels used in the design and construction of the WTC complex are shown in Figure B-2 for three ASTM-designation steels with minimum specified yield strengths of 36 ksi (A36), 50 ksi (A441), and 100 ksi (A514). In general, as the yield strength of the steel increases, the yield-to-tensile-strength ratio (Y/T) also increases. For A36 steel, Y/T is approximately 0.6, whereas for A514 steel, Y/T is approximately 0.9. The yield plateau for five steels (yield points 36, 50, 65, 80, and 100 ksi) can be highly variable for structural steels, as is apparent from a comparison of the expanded initial portions of the five steels shown in Figure B-3. At the higher yield strength associated with quenched and tempered alloy steels, there may not be a distinct yield plateau; instead, the steels exhibit gradual yielding and nonlinear behavior with strain hardening.

High strain rates tend to increase the observed yield strength and tensile strength of steel, but may also reduce the ductility. There is a greater influence on the yield point than on the tensile strength. Figure B-4 compares the effect of a very high strain rate (100 in/in/sec) for a mild carbon steel with a more usual test speed of 850 micro in/in/sec. In this example, the yield point more than doubled, whereas the tensile strength was increased about 27 percent, and the Y/T ratio approached unity.

In fracture toughness tests where rapid load toughness is determined, the dynamic yield strength of certain steels can be estimated by the following equation taken from ASTM E1820 (ASTM 1999):

$$\sigma_{yd} = \sigma_{ys} + - \frac{174{,}000}{(T + 460)\log_{10}(2x10^{7}\, t)} - 27.2\ ksi \qquad \text{(B-1)}$$

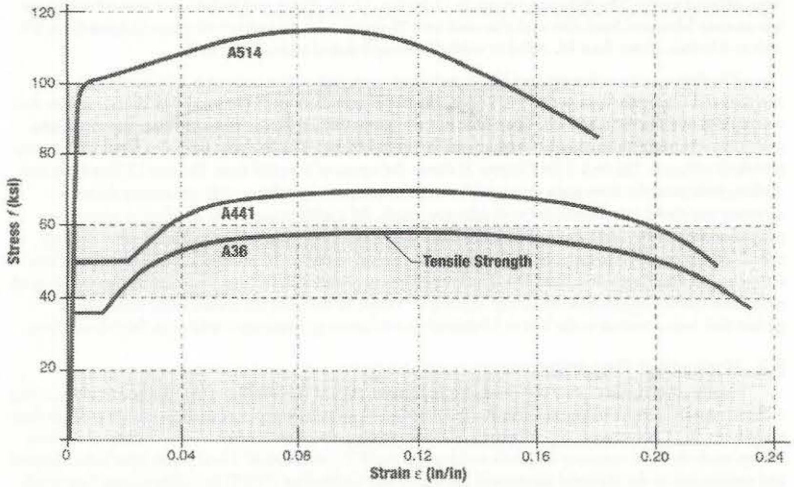


Figure B-2 Tensile stress-strain curves for three ASTM-designation steels (Brockenbrough and Johnston 1968, Tall 1974).

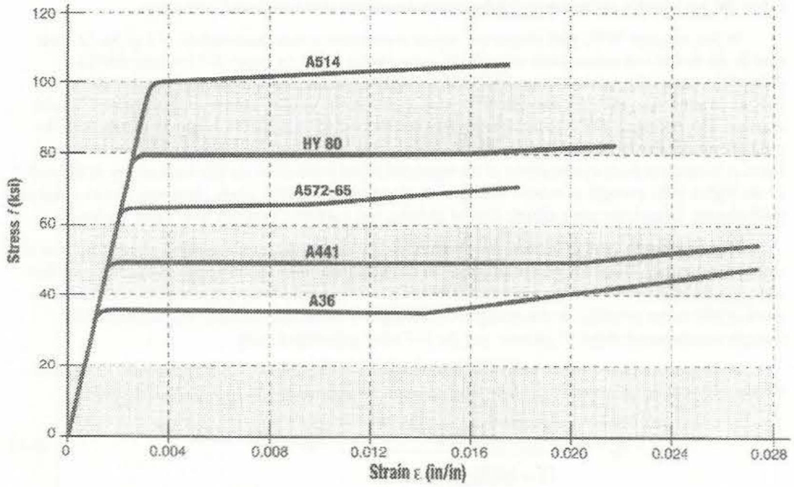


Figure B-3 Expanded yield portion of the tensile stress-strain curves (Tall 1974).

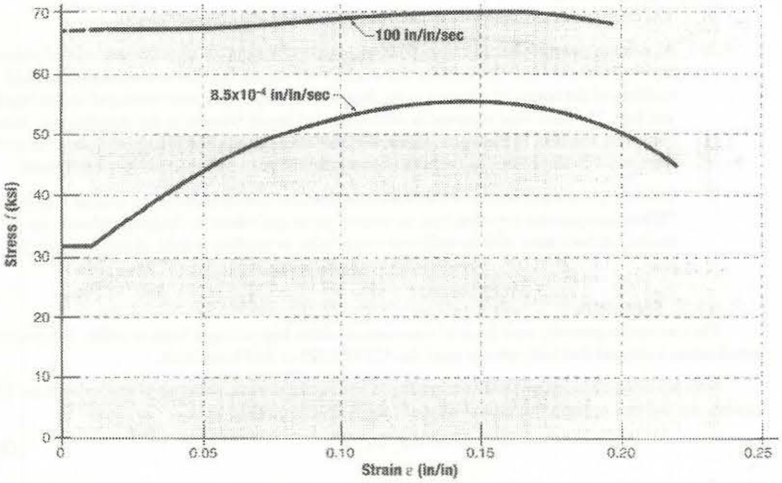


Figure B-4 Effect of high strain rate on shape of stress-strain diagram (Tall 1974).

Where σ_{ys} is room temperature static yield strength in ksi, t = loading time in milliseconds, and T is the test temperature in °F.

In *Making, Shaping, and Treating of Steel* (USX 1998), it is noted that a tenfold increase in rate of loading increased a 0.12 percent carbon steel yield strength by 7 ksi, but the influence on tensile strength was negligible.

High impacts that create notches can also lead to brittle fracture at stresses that are less than the dynamic yield strength. This is also true if triaxial stress conditions exist from constraint.

The high-temperature characteristics of structural steel are discussed in Appendix A.

B.3 WTC 1 and WTC 2 Connection Capacity

B.3.1 Background

Connections are typically designed to transfer the joint forces to which they are subjected. Generally, simple equilibrium models are used to proportion the mechanical or welded connectors and the plate or beam elements used in the connection for the required design loads (Fisher, et al. 1978; Kulak, et al. 1987; Lesik and Kennedy 1990; Salmon and Johnson 1996).

According to available information, steel connections in the WTC structures were designed in accordance with the AISC specifications that were applicable at the time to resist the required design loads. This section focuses on the ultimate limit strengths of the connectors and the various connections that were used to construct the WTC towers. Standard practice is that the design of connectors and connections provide a factor of safety of at least two against the various design strength limit states. Significant deformations can be expected when these limit states are reached.

B.3.2 Observations

1. The exterior tree columns were spliced using bolted end plate connections.
2. All column end plate bolted connections appeared to fail from the unanticipated out-of-plane bending of the column tree sections due to either the aircraft impacts or the deformation and buckling of the unbraced columns as the floor system diaphragms were destroyed by the impacts and fires. The bolts were observed to exhibit classical tensile fracture in the threaded area. Most bolts were also bent in the shank. Figure B-1 shows the column end plates and holes with some fractured and bent bolts. No evidence of plastic deformation was observed in the end plates.
3. Column splice requirements in the AISC Specifications (1963) indicated in Section 1.15.8 that "Where compression members bear on bearing plates and where tier-building columns are finished to bear, there shall be sufficient rivets, bolts, or welding to hold all parts securely in place."

B.3.3 Connectors

The connectors generally used for steel structures are either high-strength bolts or welds. The project specifications indicated that bolts were to meet the ASTM A325 or A490 standards.

Bolts are designed based on their nominal shank area A_b for tension, shear, or some combination. For tension, the nominal strength (per unit of area) of a single bolt is provided by

$$F_n = C_t F_u \tag{B-2}$$

where F_u is the minimum specified tensile strength and $C_t = 0.75$, which is the ratio of the stress area to the nominal shank area. An analysis of A325 bolts produced in the 1960s and 1970s indicated that, on average, the bolts exceeded the minimum specified tensile strength by 18 percent (Kulak, et al. 1987).

For shear, the nominal strength of a single bolt is provided by

$$F_v = C_s F_u \tag{B-3}$$

The average shear coefficient $C_s = 0.62$ for a single bolt. This coefficient is reduced to $C_s = 0.5$ to account for connection lengths up to 50 inches parallel to the line of force. When threads are not excluded from the shear plane, the coefficient C_s is further reduced to $C_s = 0.4$.

Other failure modes are possible as bolts transfer forces from one component into another by bearing and shear of the fastener. This can result in bearing deformations and net section fracture of the connected elements. Other failure modes are shear rupture or bearing strength as bolts shear connected material between the bolt and a plate edge, or block shear, which combines the tension and shear resistance of the connected elements. An example of one of these failure modes can be seen in Figure B-5, which shows a spandrel beam bolted shear connection that has failed in end zone shear as the connection was subjected to moments and/or tensile loading. This indicates that all elements in this example were at their ultimate load capacity when the spandrel connection failed.

The commonly used weld connectors are either fillet welds or groove welds. Complete joint penetration groove welds are designed for the same basic capacity as the connected base metal and match its capacity. Fillet welds and partial joint penetration groove welds are designed to resist a calculated or specified load by sizing for the weld throat area, which is the effective cross-sectional area of the weld.

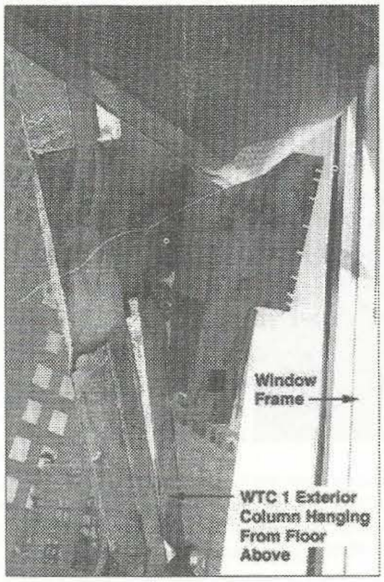


Figure B-5
Column tree showing bolt bearing shear failures of spandrel connection.

The nominal strength of a linear weld group loaded in-plane through the center of gravity is (Fisher, et al. 1978; Lesik and Kennedy, 1990).

$$F_w = 0.6\, F_{EXX}(1.0 + 0.5 \sin^{1.5} \theta) \qquad \text{(B-4)}$$

where F_{EXX} is the electrode classification number (minimum specified tensile strength) and θ is the angle of loading measured from the longitudinal axis in degrees. Hence, when the load is parallel to the weld, the capacity is 0.6 F_{EXX}, and when it is perpendicular to the longitudinal weld axis, it increases to 0.9 F_{EXX} or more. This increased strength of fillet welds transverse to the axis of loading was not recognized in the AISC Specification when the WTC was designed and built.

Figure B-6 shows the shear failure of the fillet welds that connected a built-up wide-flange column to the top end of a box core column. The basic limit states for bolts and welds described by Equations B-2, B-3, and B-4 are used in Chapter J of the AISC Load and Resistance Factor Design Specification along with resistance factors to design structural steel building connections (Fisher, et al. 1978). Additional connection strength design provisions are covered in Chapter K of the same specification for flanges and webs subjected to concentrated forces (Fisher, et al. 1978). Those relationships can also be used to assess the ultimate capacity, or strength, of structural members and connections subjected to concentrated tension and compression forces.

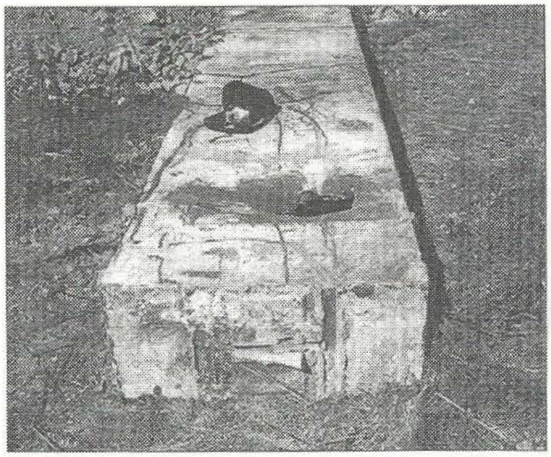


Figure B-6
Shear fracture failure of fillet welds connecting a W-shape column to a box core column.

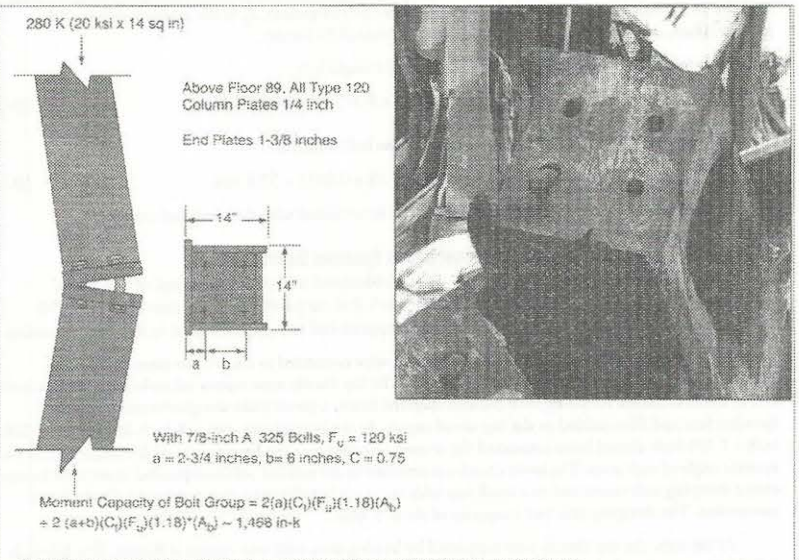
Discontinuities such as porosity and slag seldom cause a significant loss of static strength. Common imperfections are permitted within limits and accommodated by the provisions of the design standards. On the other hand, lack of fusion or cracks can have a major impact on strength and can result in joint failure at loads below the design load. This will depend on the size of the discontinuity or defect and its orientation to the applied loads.

B.4 Examples of WTC 1 and WTC 2 Connection Capacity

B.4.1 Bolted Column End Plates

Collapse of the WTC towers resulted in failure of many of the bolts in bolted end plate connections as the columns were subjected to large and unanticipated out-of-plane bending. In the majority of cases, the A325 high-strength bolts reached their tensile capacity and failed in the threaded stress area. The example shown in Figure B-7 examines the flexural capacity of the bolted end plate in a column in the impact area where the column plate thickness was 1/4 inch.

The simple moment capacity of the bolt group is 20 to 30 percent of the plastic moment capacity of a column fabricated from steels with a 50 to 100 ksi yield point, assuming no axial load in the columns. The end plates at the columns splice have a 11-3/4-inch x 14-inch cross-section. The columns are subjected to axial load from the dead load acting on the structure. For the as-built structure, the moments acting on the bolted splice are small, because the splices were located at the column inflection points and the resultant of the applied axial load and moment is within the middle third of the 12-inch-deep bearing connection. Assuming an axial stress of 20 ksi in the column, the corresponding axial force acting on the base plate is 280 kips. As the columns lose lateral support and deform out-of-plane from overloading eccentricities and from the thermal effects, the bending moment acting on the column splice does not introduce significant forces into the bolted end plate connection until the eccentricity exceeds 2 inches. As the eccentricity increases, the applied bending moment will exceed the bolt preload stress when the eccentricity reaches approximately 4 inches. Continued deformation will exceed the ultimate moment capacity of the connection and result in instability as the eccentricity approaches 4.5 inches.


280 K (20 ksi x 14 sq in)
Above Floor 89, All Type 120
Column Plates 1/4 inch
End Plates 1-3/8 inches
14"
14"
a
b
With 7/8-inch A 325 Bolts, F_u = 120 ksi
a = 2-3/4 inches, b= 6 inches, C = 0.75
Moment Capacity of Bolt Group = 2(a)(C_t)(F_u)(1.18)(A_b)
+ 2 (a+b)(C_t)(F_u)(1.18)*(A_b) ~ 1,468 in-k

***Note:** The factor 1.18 reflects the fact that production bolts exceed the minimum specified tensile.

Figure B-7 Bent and fractured bolts at an exterior column four-bolt connection.

It also should be noted that the column splices were staggered midheight at each floor, as was illustrated in Chapter 2. As a result, two-thirds of the perimeter columns were continuous at each floor's midheight elevation. This resulted in staggered failure patterns, as the bolted end plate connections and spandrel beam connections failed during the resulting instability and collapse. The exception to this staggered pattern was the splices at mechanical floors, which were not staggered, and the bolts were supplemented with welds.

B.4.2 Bolted Spandrel Connections

Collapse of the WTC towers resulted in failure of the bolted shear splices that connected the spandrel beams together at each of the prefabricated column trees. Several modes of failure were observed in these connections. Figure B-5 showed an example of bearing strength failure of the spandrel plate. The loading appeared to be a combination of unanticipated moment and tensile loading. The following example examines the shear rupture capacity of one of the bolts. The spandrel plate thickness was assumed to be 3/8 inch, which was observed at the columns with 1/4-inch plate used in Figure B-7.

The ultimate bearing strength capacity is given by (AISC 2001; Fisher, et al. 1978)

$$R_u = L_c\, t\, F_u \leq 3.0\, dt\, F_u \leq F_v\, A_s \qquad \text{(B-5)}$$

where d is the nominal bolt diameter (7/8 inch), L_c is the clear distance, in the direction of force, between the edge of the hole and the edge of the spandrel plate (1-5/16 inches), F_u is the tensile strength of the spandrel plate, and t is the thickness of the spandrel plate (0.375 inch).

This results in the following bearing capacity of a single bolt

$$R_u = L_c t F_u = 1.3125 \times 0.375 \times 90 = 44.3 \ kips \tag{B-6}$$

This is well below the single shear capacity of the bolt, which is

$$F_v A_s = 0.62 \times 120 \times 1.18 \times 0.6013 = 52.8 \ kips \tag{B-7}$$

Hence, the failure mode observed in Figure B-5 is consistent with the predicted capacity.

B.4.3 Floor Truss Seated End Connection at Spandrel Beam and Core

The floor system supported by 29-inch-deep prefabricated steel trusses consisted of 4 inches of lightweight concrete fill on a 1-1/2-inch corrugated deck that ran parallel with the truss (PATH-NYNJ 1976). As noted in the introduction, alternate truss supports had two joists attached to the seat connection.

Figure B-8 shows the end of the top chords that were connected to every other exterior column/spandrel beam and the core support channel beams. The top chords were supported on bearing seats at each end of the two trusses. At the exterior column/spandrel beam, a gusset plate was groove-welded to the spandrel face and fillet-welded to the top chord angles. At the bearing seat, two 5/8-inch A325 bolts in 3/4-inch x 1-1/4-inch slotted holes connected the trusses' top chords to the bearing seat with a single bolt in the exterior angle of each truss. The lower chord was attached to the exterior column/spandrel beam with a visco-elastic damping unit connected to a small seat with two 1-inch A490 bolts that provided a slip-resistant connection. The damping unit had a capacity of about 5 kips.

At the core, the top chords were supported by bearing seats with two vertical stiffeners. Two 5/8-inch A325 bolts were installed in 3/4-inch x 1-3/4-inch slotted holes in the seat plate and standard holes in the top chord outside angles.

Figure B-9 shows several of the failure modes of the truss connections to the chord bearing seat and spandrel beam. The gusset plate welded to the spandrel beam and the top chord failed by tensile fracture of the plate. The gusset plate connection was primarily resisting the floor diaphragm support to the column. After fracture, the slotted holes in the seat would allow rigid body motion of the trusses until the 5/8-inch bolts came into bearing. That resulted in partial fracture in the seat of the fillet welds attaching the fill plate to the spandrel beam. The seat angle welded connection to the fill plate remained intact as this separation occurred and final block shear failure developed in the outstanding angle leg at the two slotted bolt holes.

The capacity of the 3/8-inch x 4-inch A36 steel gusset plate can be estimated as:

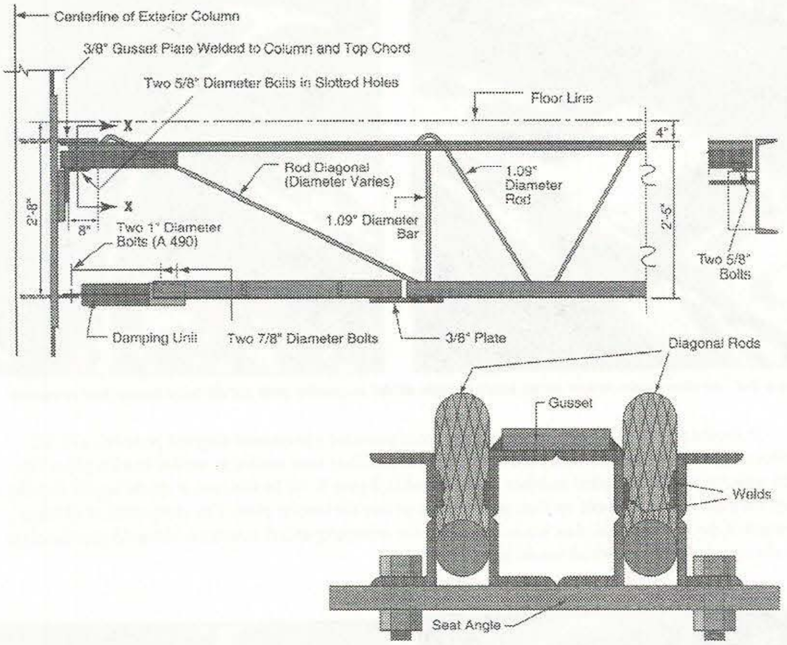
$$R_u = A_g F_u = (1.5 \ inches^2)\,(60 \ ksi) = 90 \ kips \tag{B-8}$$

The bearing capacity of the two 5/8-inch bolts connecting the top chord angles to the seat angle is

$$R_u = 2L_c t F_u = 2(1 \ inch)(0.375 \ inch)(60 \ ksi) = 45 \ kips \tag{B-9}$$

The shear capacity of the two 5/8-inch A325 bolts is

$$2 F_v A_x = 2 \times 0.62 \times 120 \times 1.18 \times 0.307 = 53.9 \ kips \tag{B-10}$$


Centerline of Exterior Column
3/8" Gusset Plate Welded to Column and Top Chord
Two 5/8" Diameter Bolts in Slotted Holes
Floor Line
X
X
4"
Rod Diagonal (Diameter Varies)
1.09" Diameter Rod
1.09" Diameter Bar
2'-8"
8"
Two 1" Diameter Bolts (A 490)
2'-5"
Two 5/8" Bolts
Damping Unit
Two 7/8" Diameter Bolts
3/8" Plate
Diagonal Rods
Gusset
Welds
Seat Angle

Section X-X

Figure B-8 Typical truss top chord connections to column/spandrel beam and to the core beam.

The block shear rupture strength provided in Chapter J of the AISC LRFD specification (Fisher, et al. 1978) can be used to assess the tensile force that separated the floor joist from the bearing seat

$$R_u = 0.6\,F_u A_{nv} + F_u A_{nt} \qquad \text{(B-11)}$$

where A_{nv} is the net shear area = 0.375 inch x 1.5 inches = 0.5632 inch^2.

The net tension area $A_{nt} = A_{nv}$. Hence, assuming an average tensile strength for A36 steel of Fu = 60 ksi results in a maximum resisting force

$$R_u = 2[0.6\,(60)(0.563) + 60\,(0.563)] = 108\ \textit{kips} \qquad \text{(B-12)}$$

It is probable that, once the 3/8-inch gusset plate fractures, the next lower bound resistance is provided by the bearing capacity of the two 5/8-inch bolts on the beam seat angle. This failure also tore off the ends of the angle even though the tensile capacity of those segments was predicted to be higher.

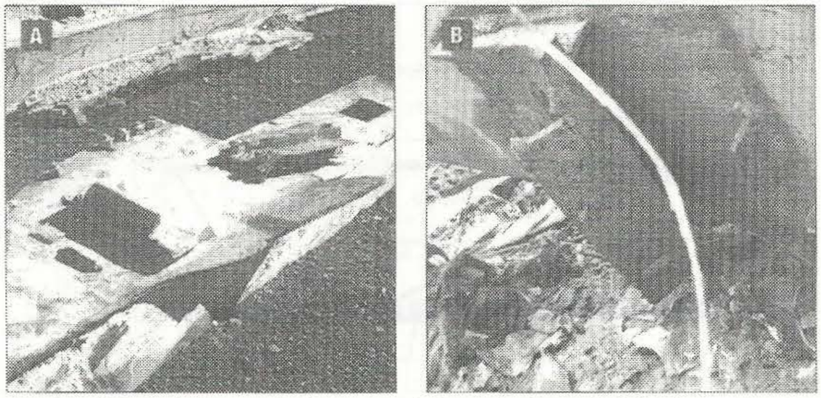


Figure B-9 (A) Visco-elastic damper angles bolted to angle welded to spandrel plate and (B) failed bearing seat connection.

It should also be noted that each truss top chord provided a horizontal diagonal plate brace (1-1/2 inches x 1/2 inch) to the two adjacent columns. These members were welded to welded bracket plates on each adjacent column/spandrel member, as illustrated in Figure B-10. In this case, it would appear that the diagonal plate braces fractured on their gross section or tore the bracket plate. The component of ultimate strength of the two diagonal plate braces normal to the column/spandrel member is about 85 percent of the tensile capacity of braces, which would be 76 kips.

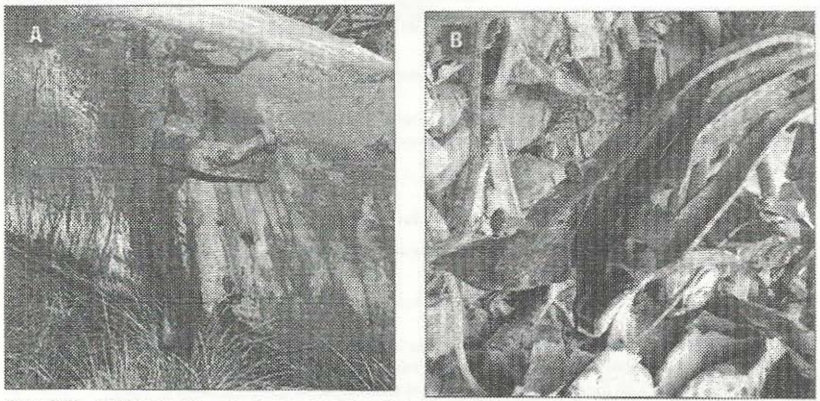


Figure B-10 (A) Bracket plate welded to the column/spandrel plate and (B) horizontal plate brace with shear connectors welded to the failed bracket.

Many of the bearing seat brackets and the damper angle connections on the column/spandrel beam plate were completely sheared off. Only the weld segments remained on face of the column/spandrel beam plate (Figure B-11). This mode of failure appears to be due to excessive vertical overloads on the floor system. This is in contrast with the failure mode exhibited in Figure B-9 where the bearing seat bracket has pulled away from the column/spandrel plate, after fracture of the top chord gusset plate.

B.4.4 WTC 5 Column-Tree Shear Connections

Chapter 4, Section 4.3.2, noted that limited structural collapse had occurred in WTC 5 as a result of failure at the shear connections between the infill beams and the column tree beam stub cantilevers. It is visually apparent from Figures 4-18, 4-19, 4-20, and 4-21 that the fire-weakened structural members formed diagonal tension field failure mechanism in the cantilever beam webs and plastic hinge moments in the cantilever beam near the column face. The following analysis examines the capacity of the cantilever beams and the shear connections between the cantilever and the infill beams.

The magnitude of the shear force acting at the end of the cantilever section can be estimated from the plastic moment capacity and the plastic shear yield capacity (AISC 2001). The plastic moment capacity of a W24x61 steel section is

$$M_p = F_y Z_x \tag{B-13}$$

and the shear yield capacity is

$$V_p = 0.6 F_y d t_w \tag{B-14}$$

where $F_y = 40$ ksi is the approximate yield strength of the A36 steel sections at room temperature, Z_x is the plastic section modulus, d is the beam depth, and t_w is the web thickness.

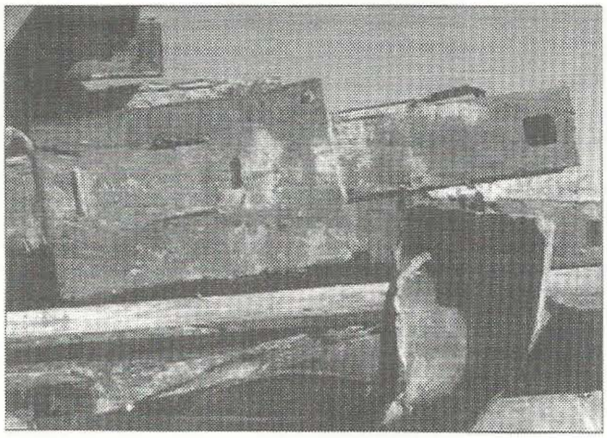


Figure B-11
Shear failure of floor truss connections from column/spandrel plate.

The vertical shear capacity of the bolted double shear splice connecting the W18x50 section to the W24x61 cantilever can be estimated for the three-bolt connection from the bearing strength relationship given in Section B.4.2. This gives

$$V_u = 3\,R_n = 3(3.0\,d_b\,t_w\,F_u) \tag{B-15}$$

where d_b = 3/4 inch is the bolt diameter, t_w = 3/8 inch is the web thickness for a W18x50, and F_u = 60 ksi is the approximate tensile strength of A36 steel.

Appendix A indicates the yield strength is 0.9 F_y at 200 °C (392 °F) and the yield strength is 0.5 F_y at 550 °C (1,022 °F). The large plastic deformation observed in the cantilever beam segments suggests that a significant loss of strength developed due to the fire. The fire temperatures reached in WTC 5 are not known, but if it is assumed for the purposes of this analysis that 550 °C (1,022 °F) was reached, this analysis estimates the cantilever plastic moment capacity as

Room Temperature: $M_p = 1.0\,F_y\,Z_x = 1.0\,(40)\,(152) = 6{,}080$ in-k (B-16a)

550 °C (1,022 °F): $M_p = 0.5\,F_y\,Z_x = 0.5\,(40)\,(152) = 3{,}040$ in-k (B-16b)

This corresponds to a shear force of about 126 kips at room temperature acting at the end of the 4-foot cantilever, which would be reduced to 63 kips at 550 °C (1,022 °F). The limiting shear yield strength of the cantilever is

Room Temperature: $V_p = 0.6\,(1.0 \times 40)\,(23)\,(0.419) = 240$ kips (B-17a)

550 °C (1,022 °F): $V_p = 0.6\,(0.5 \times 40)\,(23)\,(0.419) = 120$ kips (B-17b)

assuming the full web is effective. Hence, the three-bolt capacity is

Room Temperature: $V_u = 3[3(0.75)(0.375)(60)] \cong 152$ kips (B-18a)

550 °C (1,022 °F): $V_u = 3[3(0.75)(0.375)(30)] \cong 76$ kips (B-18b)

The double shear capacity of the three 3/4-inch high-strength bolts is

Room Temperature: $R_u = 3[2(0.62)(1.0)(1.18\,F_{ub})(A_b)] \cong 232$ kips (B-19a)

550 °C (1,022 °F): $R_u = 3[2(0.62)(0.5)(1.18\,F_{ub})(A_b)] \cong 116$ kips (B-19b)

where F_{ub} = 120 ksi is the bolt tensile strength at room temperature (see Section B.3.3) and A_b = 0.4418 square inch is the bolt area. At 550 °C (1,022 °F), the bolt tensile strength is approximately $0.51(1.18\,F_{ub}) \cong 71$ ksi.

This verifies that the bolted shear connections have sufficient capacity to develop the reduced plastic moment capacity of the fire-weakened steel beam cantilever and sustain large vertical deformation.

The failures all appear to be a result of the large tensile force that developed in the structural system during the fire and/or as the structure cooled. As demonstrated in Section B.4.2, the tensile capacity of the bolted shear splice in the beam web can be estimated for a bolt as

$$R_u = L_e t\,F_u \leq 3\,d\,t\,F_u \tag{B-20}$$

with L_e = 1.344 inches is the edge distance, t = 0.375 inch is the plate thickness in bearing, and F_u is the applicable tensile strength.

Room Temperature: $R_u = (1.344)\,(0.375)\,(60) = 30$ kips/bolt (B-21a)

550 °C (1,022 °F): $R_u = (1.344)\,(0.375)\,(30) = 15$ kips/bolt (B-21b)

The photographs in Figure 4-22, in Chapter 4, indicate that the deformed structure subjected the bolted shear connection to a large tensile force. At 550 °C (1,022 °F), the ultimate resistance of the three bolts is about 45 kips. The capacity increases to about 90 kips at room temperature. Failure occurred between these bounds.

Tensile catenary action of this type of floor framing members and their connections has not been a design requirement or consideration for most buildings. For the analysis shown here, with assumed fire temperatures, increasing the end distance L_e to 2.25 inches would increase the tensile capacity of the three bolts to about 76 kips at 550 °C (1,022 °F) and 152 kips at room temperature, because the resistance would increase to the limit in Equation B-20.

B.5 References

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Jonathan Barnett
Ronald R. Biederman
R. D. Sisson, Jr.

C Limited Metallurgical Examination

C.1 Introduction

Two structural steel members with unusual erosion patterns were observed in the WTC debris field. The first appeared to be from WTC 7 and the second from either WTC 1 or WTC 2. Samples were taken from these beams and labeled Sample 1 and Sample 2, respectively. A metallurgic examination was conducted.

C.2 Sample 1 (From WTC 7)

Several regions in the section of the beam shown in Figures C-1 and C-2 were examined to determine microstructural changes that occurred in the A36 structural steel as a result of the events of September 11, 2001, and the subsequent fires. Although the exact location of this beam in the building was not known, the severe erosion found in several beams warranted further consideration. In this preliminary study, optical and scanning electron metallography techniques were used to examine the most severely eroded regions as exemplified in the metallurgical mount shown in Figure C-3. Evidence of a severe high temperature corrosion attack on the steel, including oxidation and sulfidation with subsequent intergranular melting, was readily visible in the near-surface microstructure. A liquid eutectic mixture containing primarily iron, oxygen, and sulfur formed during this hot corrosion attack on the steel. This sulfur-rich liquid penetrated preferentially down grain boundaries of the steel, severely weakening the beam and making it susceptible to erosion. The eutectic temperature for this mixture strongly suggests that the temperatures in this region of the steel beam approached 1,000 °C (1,800 °F), which is substantially lower than would be expected for melting this steel.

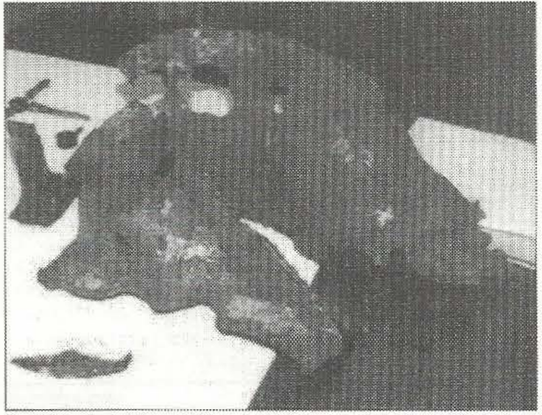


Figure C-1 Eroded A36 wide-flange beam.

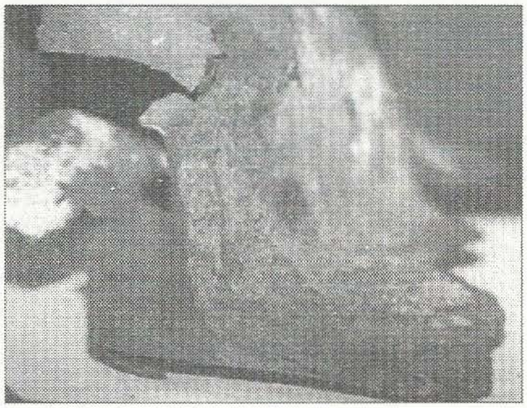


Figure C-2
Closeup view of eroded wide-flange beam section.

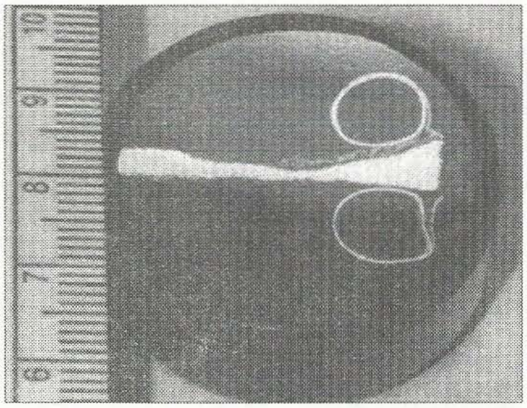


Figure C-3
Mounted and polished severely thinned section removed from the wide-flange beam shown in Figure C-1.

When steel cools below the eutectic temperature, the liquid of eutectic composition transforms to two phases, iron oxide, FeO, and iron sulfide, FeS. The product of this eutectic reaction is a characteristic geometrical arrangement that is unique and is readily visible even in the unetched microstructure of the steel. Figures C-4 and C-5 present typical near-surface regions showing the microstructural changes that occur due to this corrosion attack. Figure C-6 presents the microstructure from the center of a much thicker section of the steel that is unaffected by the hot corrosion. Figure C-7 illustrates the deep penetration of the liquid into the steel's structure. In order to identify the chemical composition of the eutectic, a qualitative chemical evaluation was done using energy dispersive X-ray analysis (EDX) of the eutectic reaction products. Figure C-8 illustrates the results of this analysis.

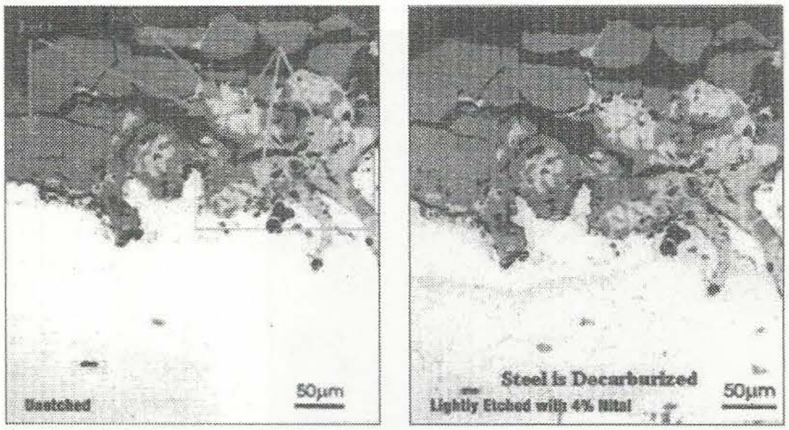

Unetched
50μm
Steel is Decarburized
Lightly Etched with 4% Nital
50μm

Figure C-4 Optical microstructure near the steel surface.

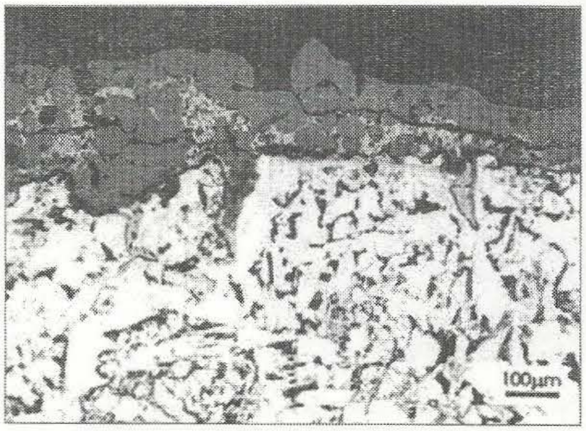


Figure C-5 Another hot corrosion region near the steel surface (etched with 4 percent nital). (Note: (1) Oxide rounding where the FeO-FeS eutectic product is present. (2) Reduction in banding of the steel when re-transformation occurs on cooling from austenite to ferrite and pearlite.)

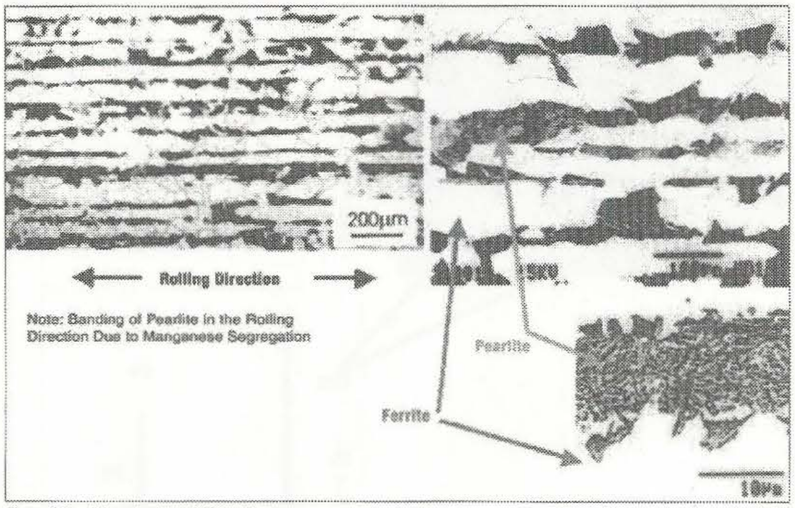

200µm
Rolling Direction
Note: Banding of Pearlite in the Rolling Direction Due to Manganese Segregation
Pearlite
Ferrite
10µm

Figure C-6 Microstructure of A36 steel.

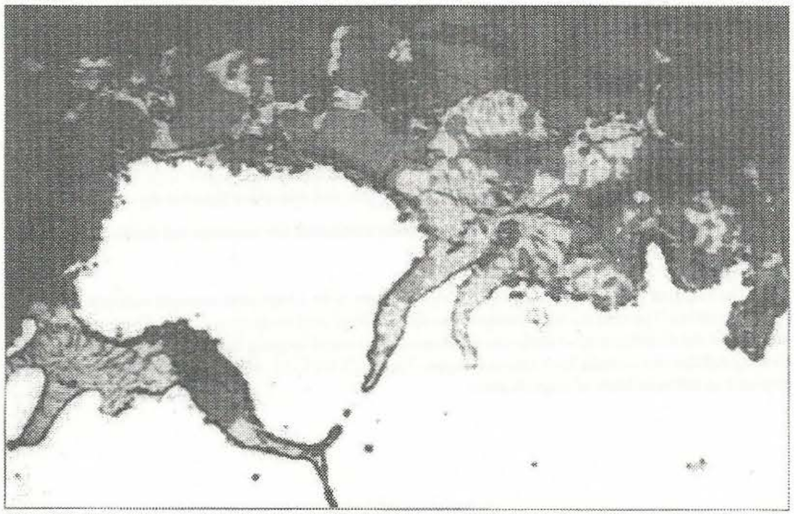


Figure C-7 Deep penetration of liquid into the steel. (Note: Hot corrosion of the steel can produce "islands" of steel surrounded by liquid, which will make erosion of the steel much easier.)

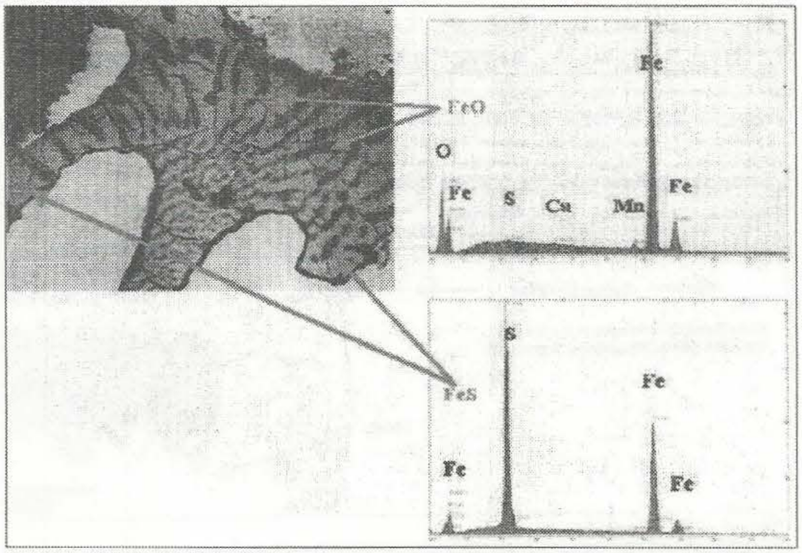


Figure C-8 Qualitative chemical analysis.

C.3 Summary for Sample 1

1. The thinning of the steel occurred by a high-tempertture corrosion due to a combination of oxidation and sulfidation.
2. Heating of the steel into a hot corrosive environment approaching 1,000 °C (1,800 °F) results in the formation of a eutectic mixture of iron, oxygen, and sulfur that liquefied the steel.
3. The sulfidation attack of steel grain boundaries accelerated the corrosion and erosion of the steel.

C.4 Sample 2 (From WTC 1 or WTC 2)

The origin of the steel shown in Figure C-9 is thought to be a high-yield-strength steel removed from a column member. The steel is a high-strength low-alloy (HSLA) steel containing copper. The unusual thinning of the member is most likely due to an attack of the steel by grain boundary penetration of sulfur forming sulfides that contain both iron and copper. Figures C-10, C-11, and C-12 show the region of severe corrosion at different levels of magnification.

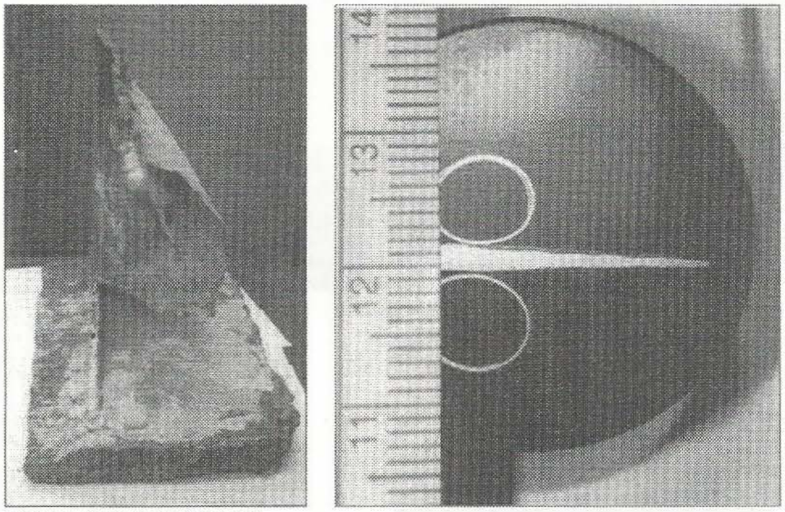


Figure C-9 Qualitative chemical analysis.

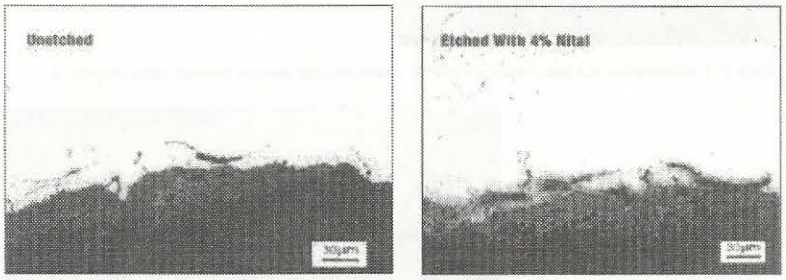

Unetched
Etched With 4% Nital

Figure C-10 Grain boundary corrosion attack.

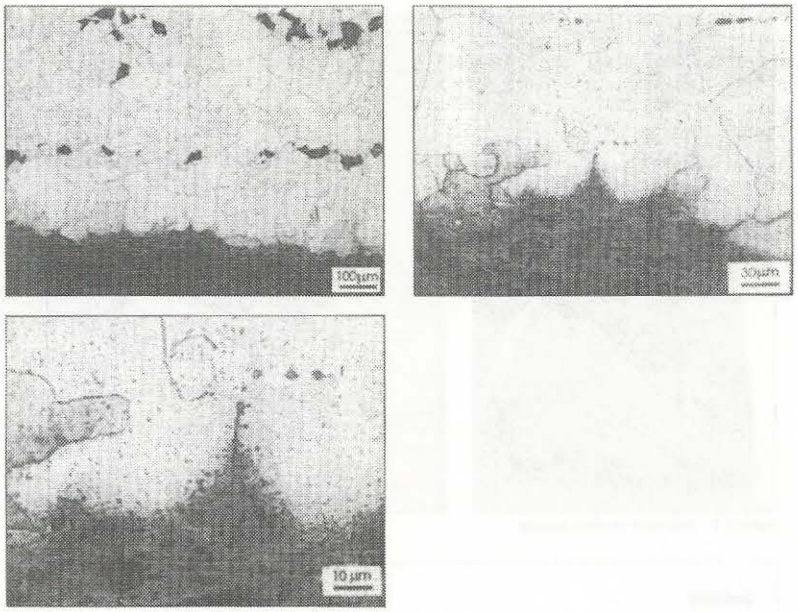

100µm
30µm
10 µm

Figure C-11 Microstructure of a typical region showing the surface and grain boundary corrosion attack of Sample 2.

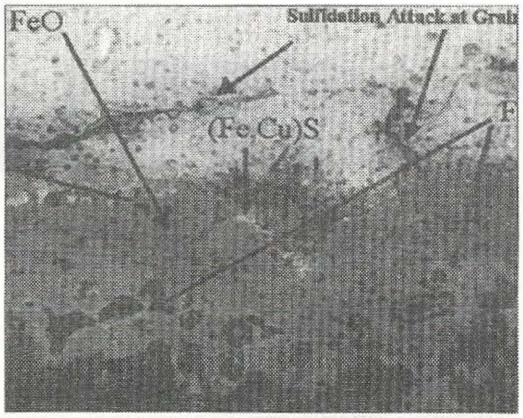

FeO
Sulfidation Attack at Grai
(Fe,Cu)S
F

Figure C-12
Higher magnification of the region shown in Figure C-10.

Figure C-13 shows the region where a qualitative chemical analysis of the eroded region was performed. The comparison of the EDX spectra from the specific regions identified in Figure C-13 shows concentration of copper and sulfur in the grain boundaries in addition to iron sulfide formation adjacent to iron oxide in the oxidized surface layer. Sulfide formation within the steel microstructure increases in concentration as the oxidized region is approached from the steel side. This is clearly shown in Figure C-14.

The larger sulfides further into the steel are the more stable manganese sulfides that were formed when the steel was made. The smaller sulfides that have formed as a result of the fire do not contain significant amounts of manganese, but rather are primarily sulfides containing iron and copper. These sulfides have a lower melting temperature range than manganese sulfide. It is much more difficult to tell if melting has occurred in the grain boundary regions in this steel as was observed in the A36 steel from WTC 7. It is possible and likely, however, that even if grain boundary melting did not occur, substantial penetration by a solid state diffusion mechanism would have occurred as evidenced by the high concentration of sulfides in the grain interiors near the oxide layer. Temperatures in this region of the steel were likely to be in the range of 700–800 °C (1,290–1,470 °F).

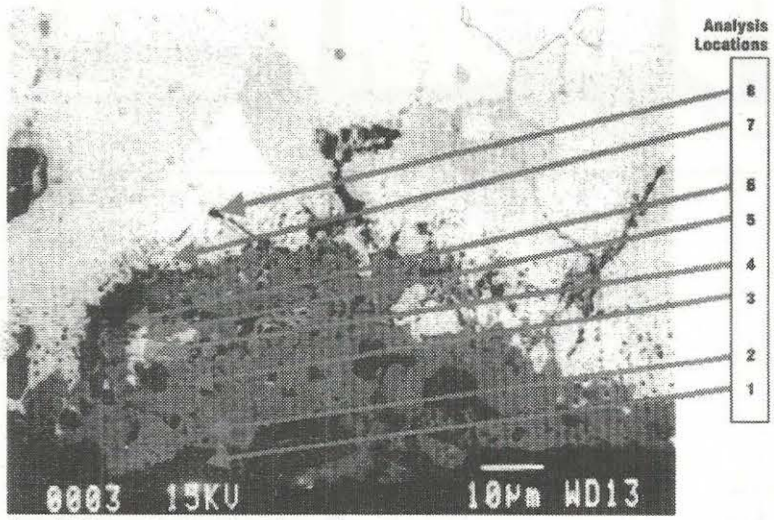
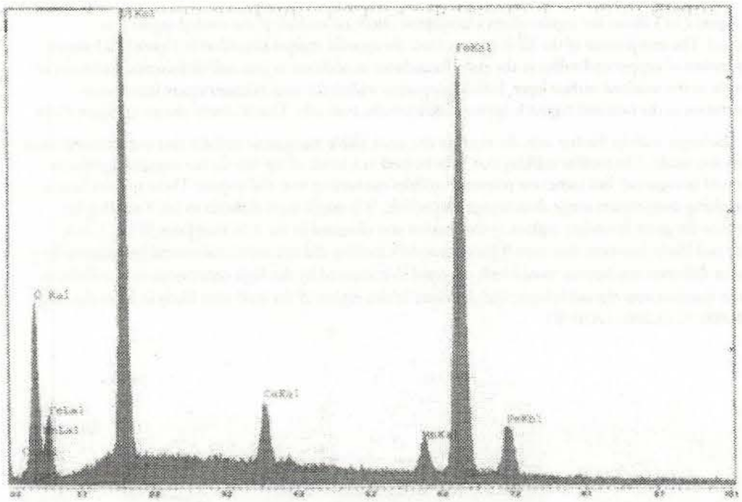
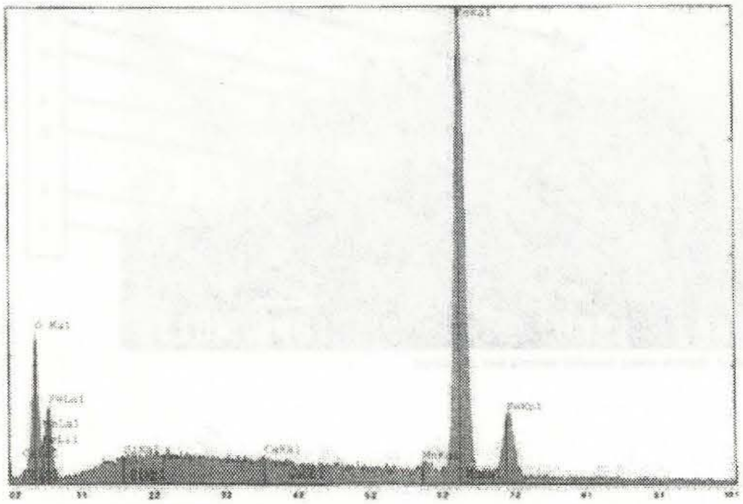


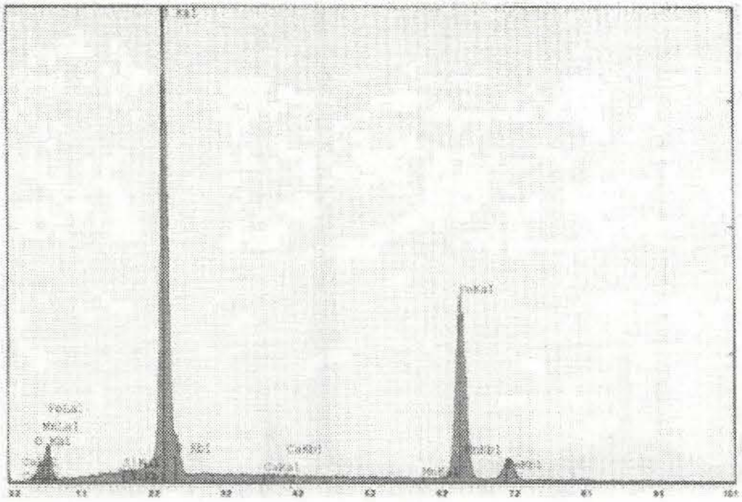
Figure C-13 Regions where chemical analysis was performed.



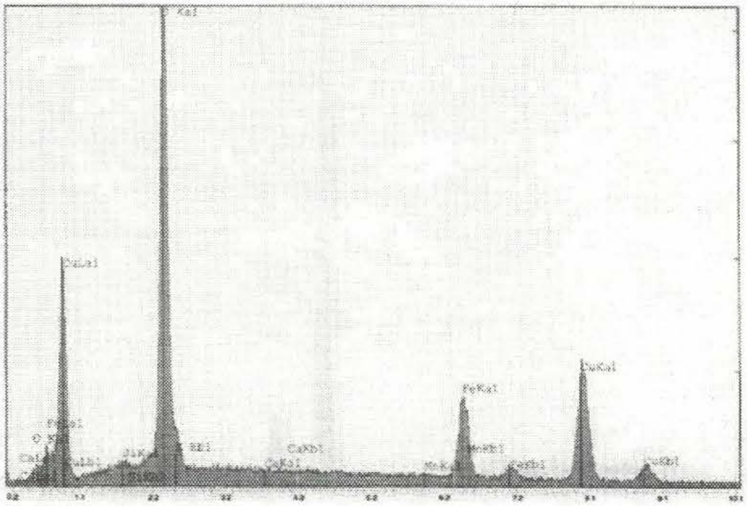
Location 1 (Figure C-13 continued).



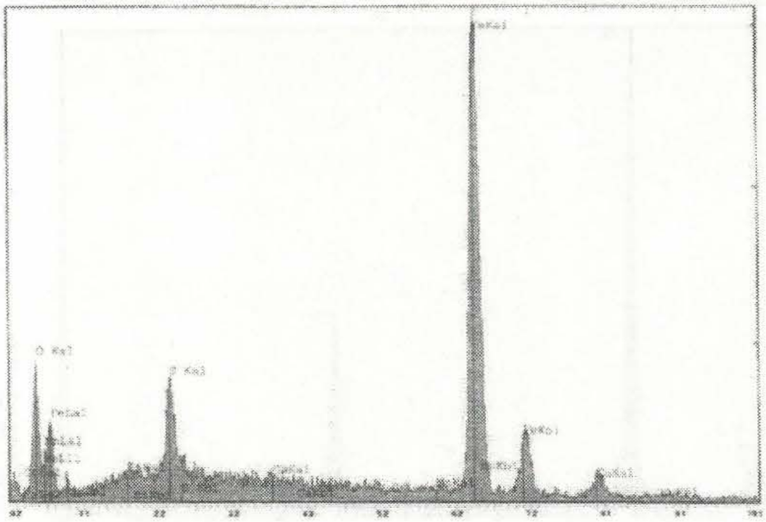
Locations 2 and 3 (Figure C-13 continued).



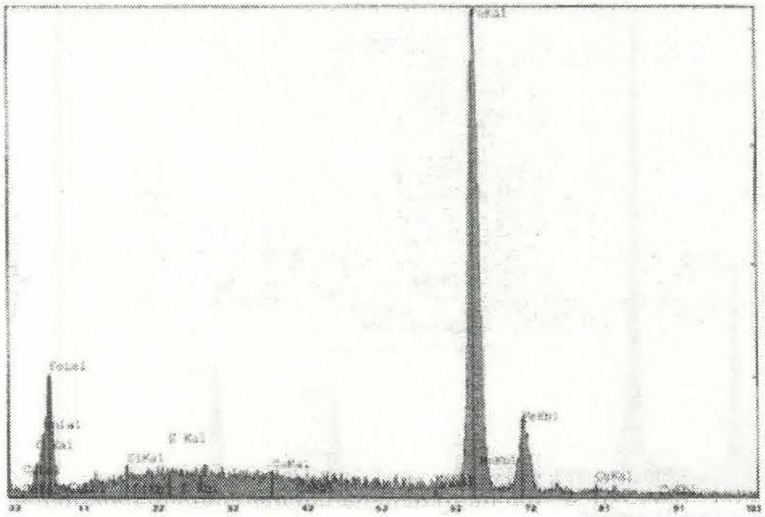
Location 4 (Figure C-13 continued).



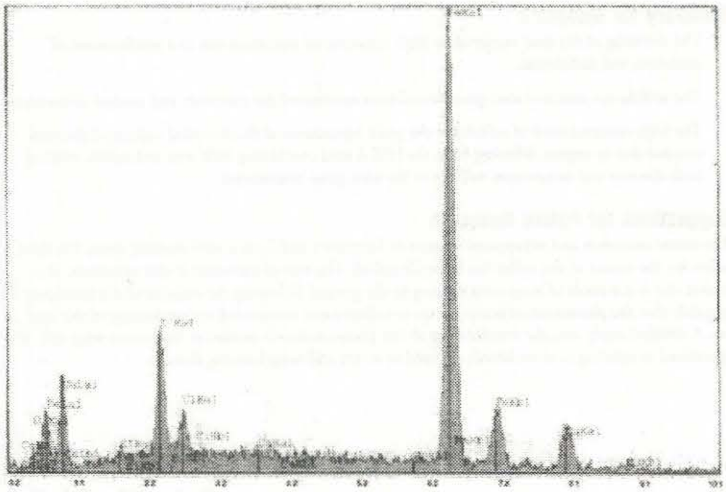
Location 5 (Figure C-13 continued).



Location 6 (Figure C-13 continued).



Location 7 (Figure C-13 continued).



Location 8 (Figure C-13 continued).

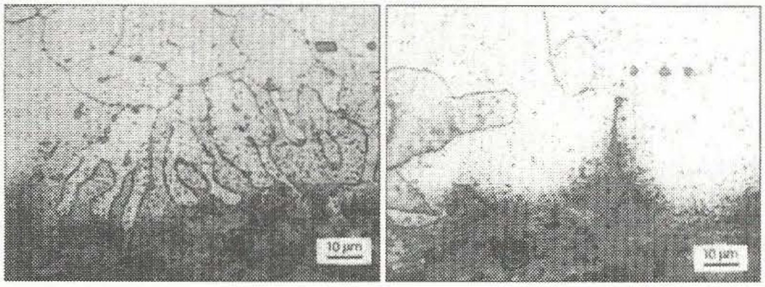


Figure C-14 Gradient of sulfides into the steel from the oxide-metal interface.

C.5 Summary for Sample 2

1. The thinning of the steel occurred by high temperature corrosion due to a combination of oxidation and sulfidation.
2. The sulfidation attack of steel grain boundaries accelerated the corrosion and erosion of the steel.
3. The high concentration of sulfides in the grain boundaries of the corroded regions of the steel occured due to copper diffusing from the HSLA steel combining with iron and sulfur, making both discrete and continuous sulfides in the steel grain boundaries.

C.6 Suggestions for Future Research

The severe corrosion and subsequent erosion of Samples 1 and 2 are a very unusual event. No clear explanation for the source of the sulfur has been identified. The rate of corrosion is also unknown. It is possible that this is the result of long-term heating in the ground following the collapse of the buildings. It is also possible that the phenomenon started prior to collapse and accelerated the weakening of the steel structure. A detailed study into the mechanisms of this phenomenon is needed to determine what risk, if any, is presented to existing steel structures exposed to severe and long-burning fires.

Ramon Gilsanz
Audrey Massa

D *WTC Steel Data Collection*

D.1 Introduction

WTC steel data collection efforts were undertaken by the Building Performance Study (BPS) Team and the Structural Engineers Association of New York (SEAoNY) to identify significant steel pieces from WTC 1, 2, 5, and 7 for further study. The methods used to identify and document steel pieces are presented, as well as a spreadsheet that documents the data for steel pieces inspected at various sites from October 2001 through March 2002.

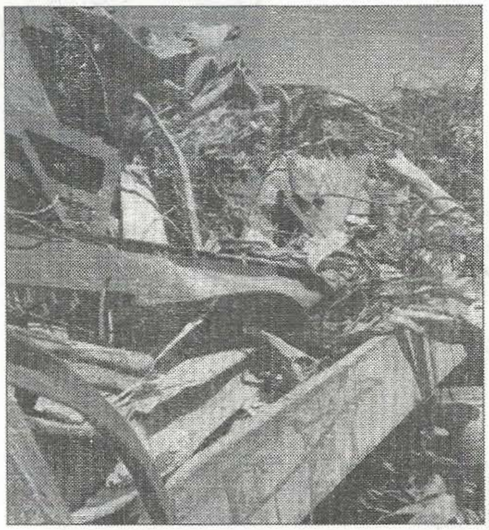
D.2 Project Background

Collection and storage of steel members from the WTC site was not part of the BPS Team efforts sponsored by FEMA and the American Society of Civil Engineers (ASCE). SEAoNY offered to organize a volunteer team of SEAoNY engineers to collect certain WTC steel pieces for future building performance studies. Visiting Ground Zero in early October 2001, SEAoNY engineers, with the assistance from the New York City Department of Design and Construction (DDC), identified and set aside some steel pieces for further study.

Of the estimated 1.5 million tons of WTC concrete, steel, and other debris, more than 350,000 tons of steel have been extracted from Ground Zero and barged or trucked to salvage yards where it is cut up for recycling. Salvage yard operations are shown in Figures D-1 through D-3. Four salvage yards were contracted to process WTC steel:

- Hugo Nue Schnitzer at Fresh Kills (FK) Landfill, Staten Island, NJ
- Hugo Nue Schnitzer's Claremont (CM) Terminal in Jersey City, NJ
- Metal Management in Newark (NW), NJ
- Blanford and Co. in Keasbey (KB), NJ

SEAoNY appealed to its membership for experienced senior engineers to visit the salvage yards on a volunteer basis, and to identify and set aside promising steel pieces for further evaluation. Seventeen volunteer SEAoNY engineers started going to the yards in November 2001. A list of engineers and others who contributed to this effort is included in Appendix G of this report.



SEAoNY

Figure D-1
Mixed, unsorted steel upon delivery to salvage yard.

As of March 15, 2002, a total of 131 engineer visits had been made to these yards on 57 separate days. An engineer visit typically ranged from a few hours to an entire day at a salvage yard. The duration of the visits, number of visits per yard, and the dates the yards were visited varied, depending on the volume of steel being processed, the potential significance of the steel pieces being found, salvage yard activities, weather, and other factors. Sixty-two engineer trips were made to Jersey City, 38 to Keasbey, 15 to Fresh Kills, and 16 to Newark. Three trips made in October included several ASCE engineers. Eleven engineer trips were made in November, 41 in December, 43 in January, 28 in February, and 5 through March 15, 2002.

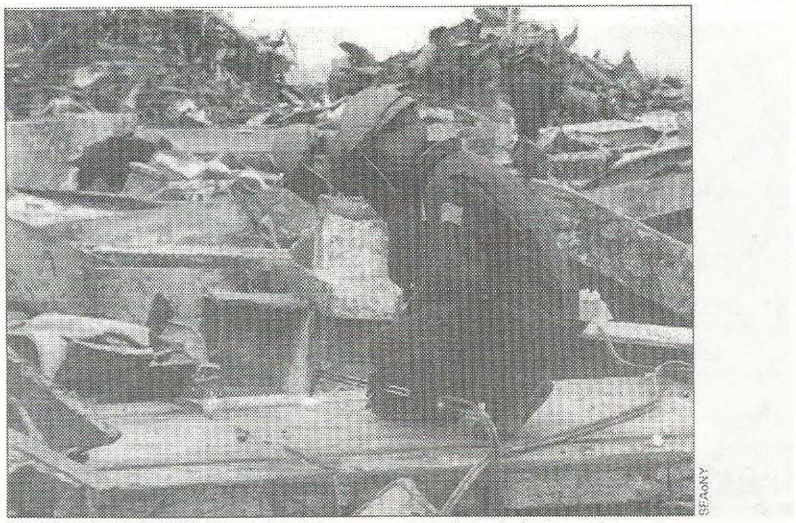
D.3 Methods

Engineers identified steel members that would be considered for evaluation or tests relative to the fire and structural response of the WTC buildings. Pieces that were measured and determined to be significant were marked to be saved, and arrangements were made to have them moved to a safe location where they would not be processed (cut up and shipped). Some pieces were not saved, but samples, called coupons, were cut from them and saved for future studies.

D.3.1 Identifying and Saving Pieces

As shown in Figure D-4, the engineers searched through unsorted piles of steel for pieces from WTC 1 and WTC 2 impact areas and from WTC 5 and WTC 7. They also checked for pieces of steel exposed to fire. Specifically, the engineers looked for the following types of steel members:

- Exterior column trees and interior core columns from WTC 1 and WTC 2 that were exposed to fire and/or impacted by the aircraft.



SEAoNY

Figure D-2 Torch cutting of very large pieces into more manageable pieces of a few tons each.

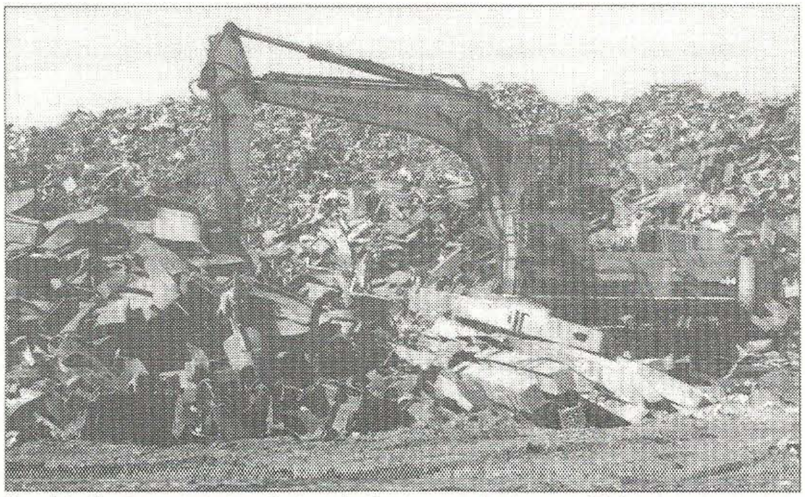
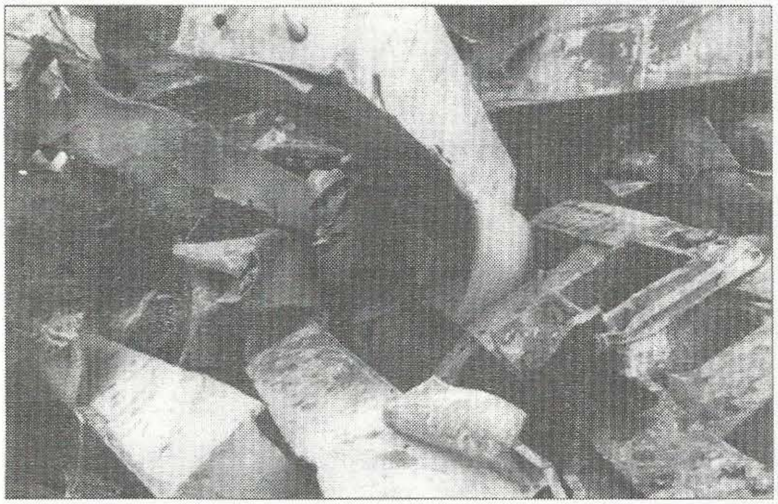


Figure D-3 Pile of unsorted, mixed steel (background) with sorted, large steel pieces (center) being lifted and cut into smaller pieces (left).



SEAoNY

Figure D-4 Engineer climbing in unprocessed steel pile to inspect and mark promising pieces.

- Exterior column trees and interior core columns from WTC 1 and WTC 2 that were above the impact zone.
- Badly burnt pieces from WTC 7.
- Connections from WTC 1, 2, and 7, such as seat connections, single shear plates, and column splices.
- Bolts from WTC 1, 2, and 7 that were exposed to fire, fractured, and/or that appeared undamaged.
- Floor trusses, including stiffeners, seats, and other components.
- Any piece that, in the engineer's professional opinion, might be useful for evaluation. When there was any doubt about a particular piece, the piece was kept while more information was gathered. A conservative approach was taken to avoid having important pieces processed in salvage yard operations.

The engineers were able to identify many pieces by their markings. Each piece of steel was originally stenciled in white or yellow with information telling where it came from and where it was going. A sample of the markings can be seen in Figure D-5.

For example, a given piece might be marked, "PONYA WTC 213.00 236B4-9 558 35 TONS." Translated, this meant the column was destined for the Port of New York Authority's World Trade Center as part of contract number 213.00. Its actual piece number was 236B, and it was to be used between floors 4 and 9 in tower B (WTC 2). Its derrick division number was 558, which determined which crane would lift it onto the building and the order in which it was to be erected. Other markings might include the name of the iron works or shipping instructions to those responsible for railway transportation (Gillespie 1999).

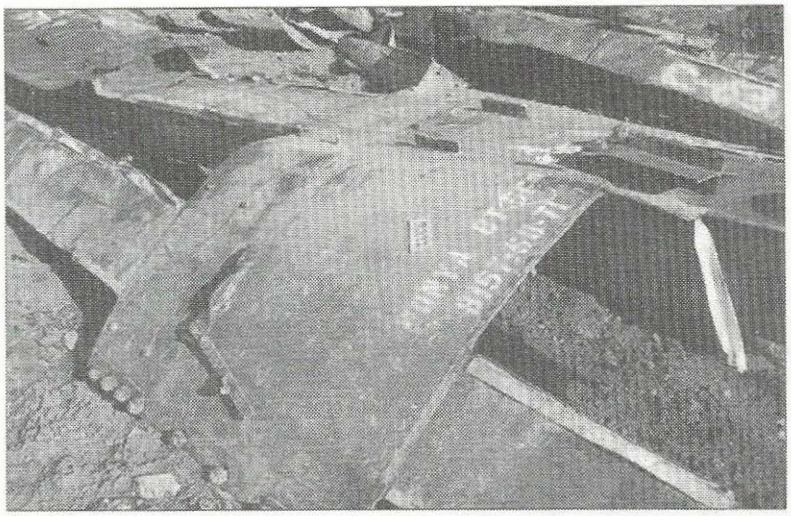


Figure D-5 Stenciled markings on WTC 2 perimeter column from floors 68–71.

Additional markings (and duplicates of stenciled markings) may sometimes be found stamped into the steel pieces. These stamped markings are about 3/4 inch tall.

In the absence of markings, member size is the quickest and easiest means for the engineers to establish an approximate original location for a piece. For example, the spandrel plates used in the column-to-column connections in the perimeters of WTC 1 and WTC 2 reportedly ranged in thickness from about 1-1/2 inches at the lower levels to as little as 3/8 inch at the upper levels.

The lighter perimeter columns from WTC 1 and WTC 2 appear to have used column-to-column connections with 4 bolts, whereas larger members presumably from lower floors used six-bolt column-to-column connections. Core column sizes vary, with some heavier sections at the lower floors having plates 4 inches thick or greater.

After a steel piece was identified for further study, it was set aside. As shown in Figure D-6, each piece was marked with spray paint, labeled "SAVE" and a piece number, such as "C-68." The engineers also advised site personnel of the location of these pieces so they would not be processed as scrap.

D.3.2 Documenting Pieces

To document the identified steel pieces of interest, the engineers measured their dimensions. They also drew sketches, and took photographs and videos of the pieces.

The steel member dimensions helped to determine the approximate building location of a piece prior to the disaster. The engineers measured and recorded dimensions using metal tape rules, vernier calipers, or other measuring devices. See Figures D-7 through D-9.

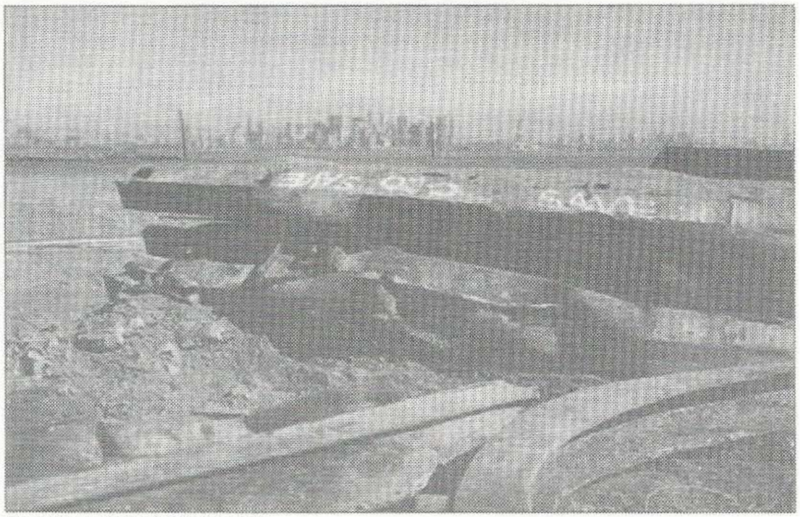


Figure D-6 Steel pieces marked "SAVE."

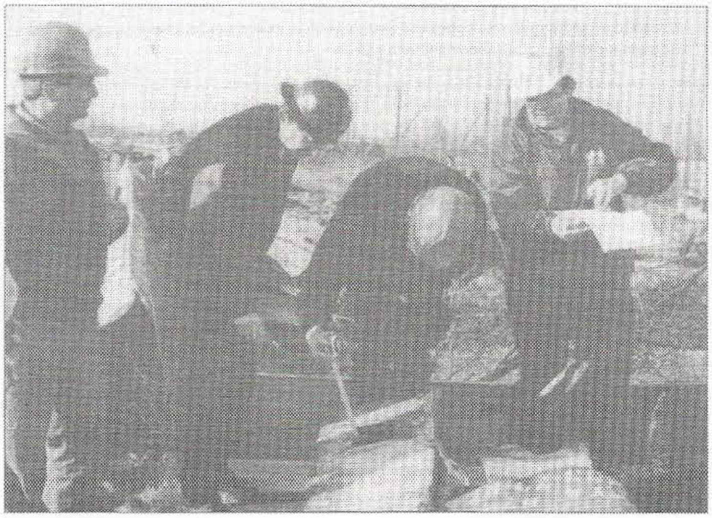


Figure D-7 Engineers measuring and recording steel piece dimensions.

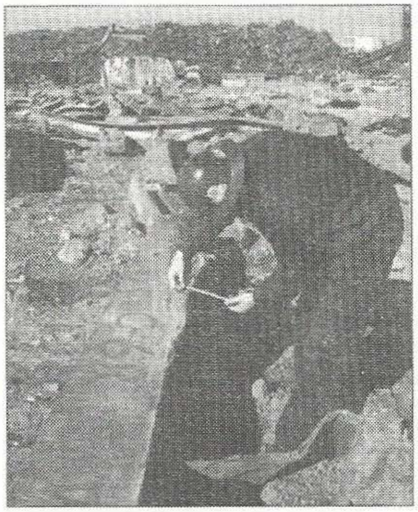


Figure D-8
Engineer measuring spandrel plate thickness (t_s).

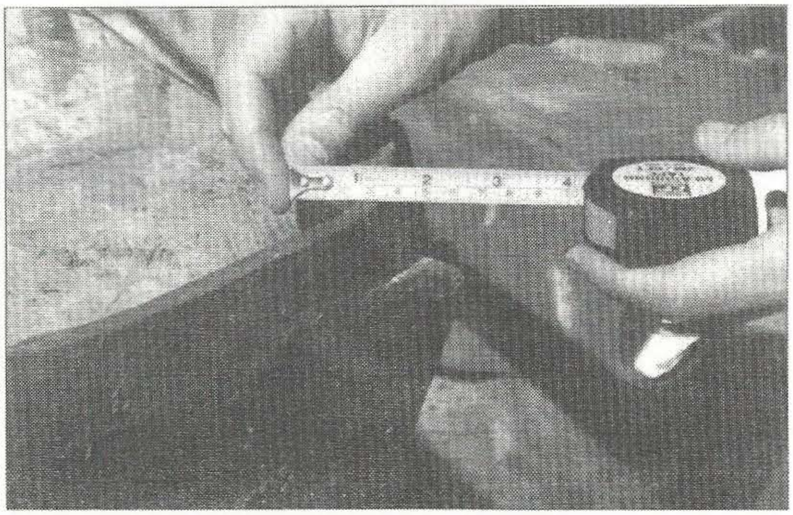


Figure D-9 Measurement of 1/4 inch for web thickness (t_w).

The measured and recorded dimensions (shown in Figure D-10) included the following:

- depth of the piece (d)
- thickness of the web (t_w)
- length of flange (b_f)
- thickness of the top flange (t_{tf})
- thickness of the bottom flange (t_{bf})
- thickness of the spandrel plate (t_s)

Note that the thickness of the spandrel plate may be different from that of the top flange.

D.3.3 Getting Coupons

Samples, or coupons, were cut by yard personnel. A coupon is a sample of steel cut from a larger portion of a steel member or piece. The collected coupons cut are intended for off-site examination in a laboratory.

Where possible, coupons were selected to yield sufficient material for a number of destructive (and mutually exclusive) tests on steel from essentially the same condition. Coupons were sized to be 12 inches by 12 inches, which is considered adequate for most purposes. Where possible, coupons included two faces of attached plates forming a portion of the member. They were also selected so that heat effects from the cutting operation did not affect the coupons' intended test areas.

Figure D-11 shows a steel piece clearly marked with spray paint that shows salvage yard personnel where to cut the coupon. A coupon that has been cut is shown in Figure D-12.

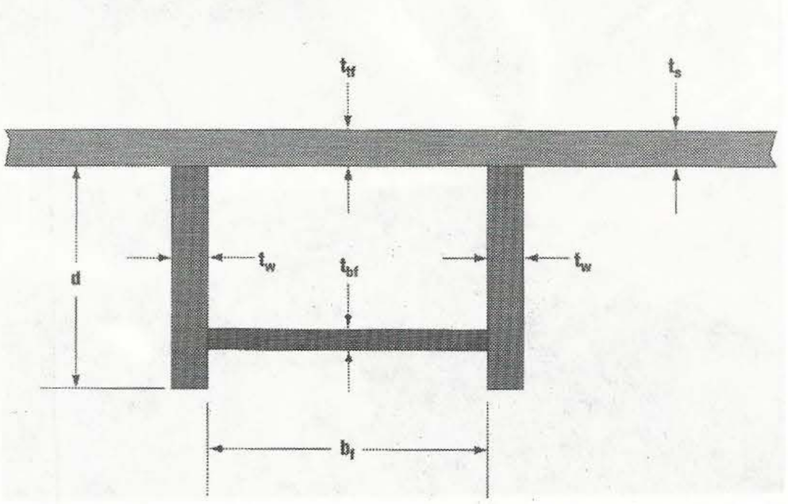


Figure D-10 Measured dimensions of the steel pieces.

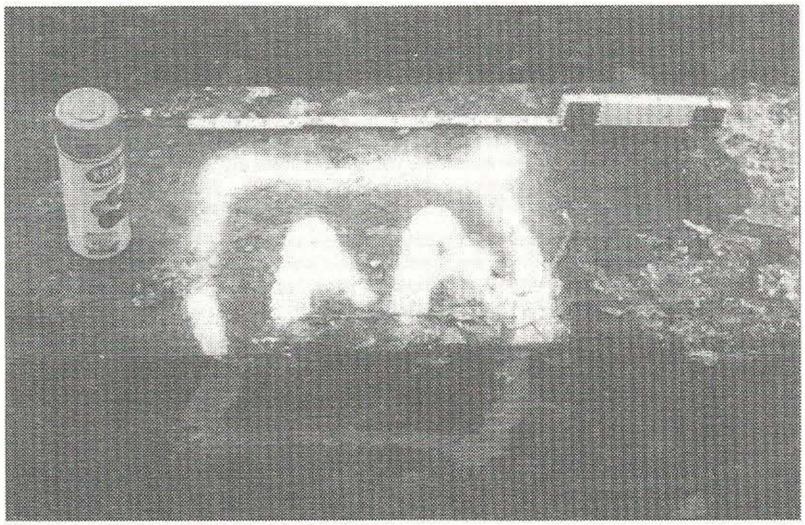


Figure D-11 Burnt steel piece marked for cutting of coupon.

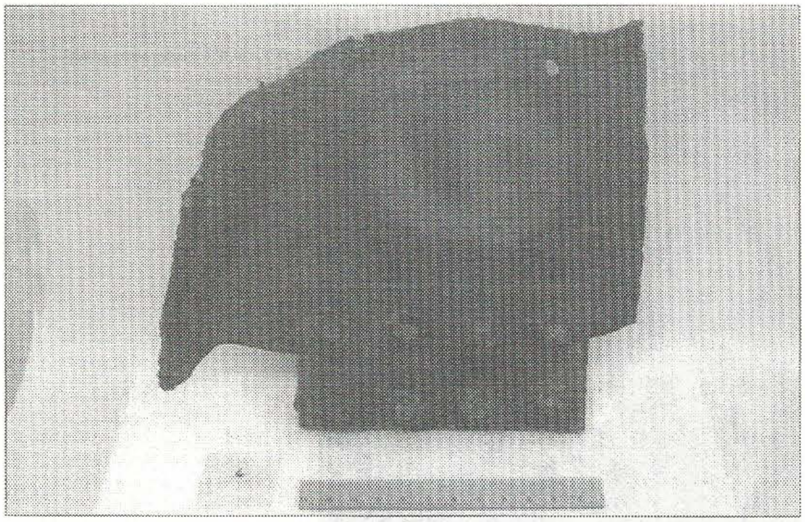


Figure D-12 Coupon cut from WTC 5 showing web tear-out at bolts.

D.4 Data Collected

The steel data are compiled in a spreadsheet that includes data from each of the four salvage yards visited by the SEAoNY and WTC BPS Team engineers (the spreadsheet is presented at the end of this appendix). The data are organized according to the salvage yard where each steel piece was examined. The data include the piece identification mark that was sprayed on the piece, the measured dimensions, a brief description of the piece indicating why the piece was selected for further evaluation, information identifying photographs and/or video taken, and the status of any coupon taken. Pieces that were searched for and inspected include perimeter or core columns near the impact area of WTC 1 or WTC 2, burnt pieces from WTC 7, and connection pieces from WTC 5 (see Figures D-12 through D-18).

The steel pieces range in size from fasteners inches in length and weighing a couple of ounces to column pieces up to 36 feet long and weighing several tons. As of March 15, 2002, a total of 156 steel pieces (not including most of the fasteners and other smaller pieces) had been inspected. In addition, seven pieces were set aside from Ground Zero with assistance from the DDC.

It is important to note that the quality of the pieces, rather than the number of pieces, is significant to this study. Not all of these pieces were kept for further study. This is because:

- some pieces were later determined not to be relevant to understanding building damage;
- once a coupon was taken, the full piece was discarded; and
- pieces were accidentally processed in salvage yard operations before they were removed from the yards for further study.

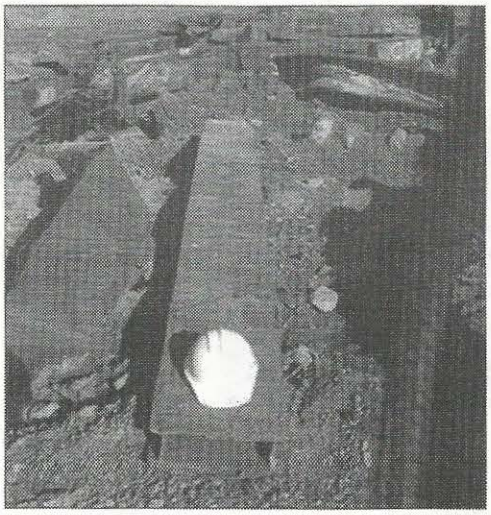


Figure D-13
WTC 1 or WTC 2 core column (C-74).

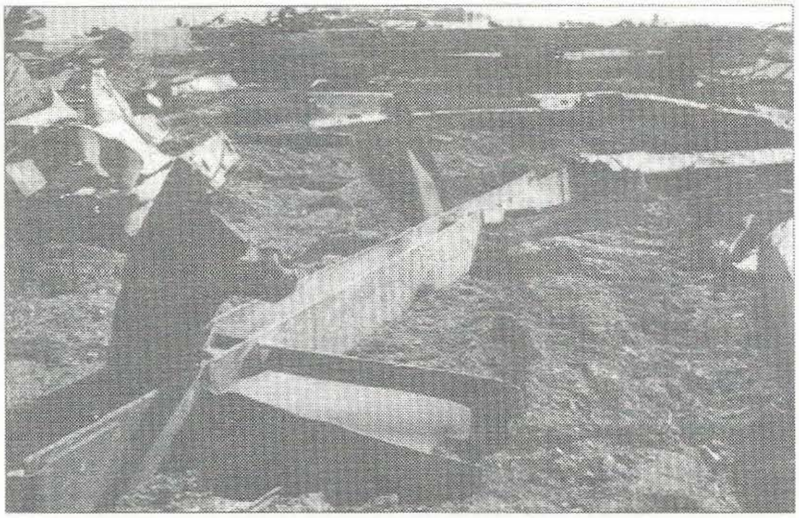


Figure D-14 WTC 7 W14 column tree with beams attached to two floors.

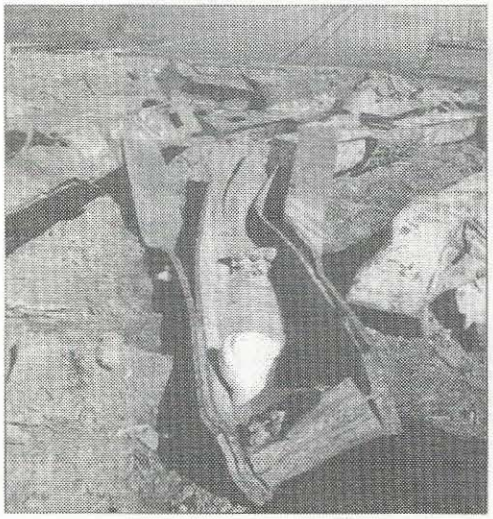


Figure D-15
Built-up member with failure along stitch welding.

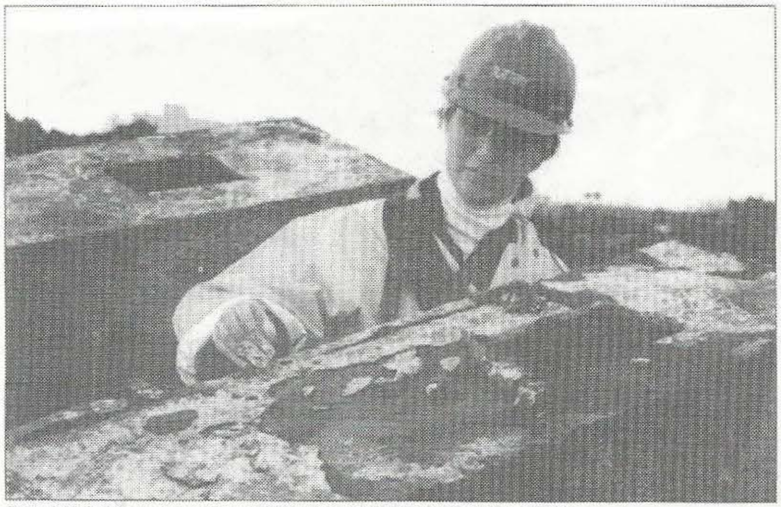
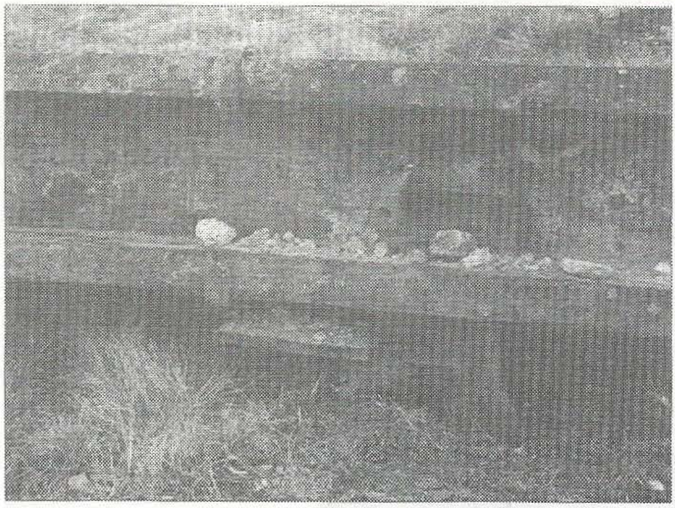
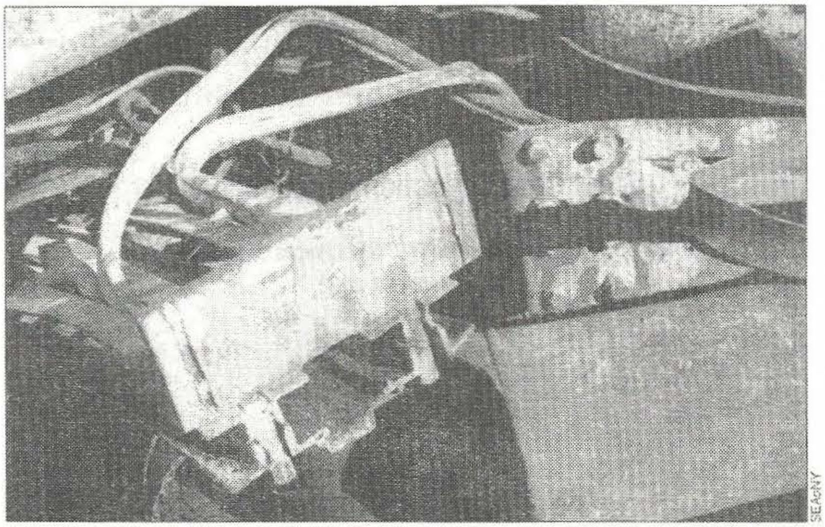


Figure D-16 Engineer inspecting fire damage of perimeter column tree from WTC 1 or WTC 2.



SEAoNY

Figure D-17 Seat connection in fire-damaged W14 column from WTC 7.



SEAoNY

Figure D-18 WTC 1 or WTC 2 floor-truss section with seat connection fractured along welds.

It was expected that most steel members from the impact zones would have reached the yards early in the WTC site excavation process because pieces from the higher floors would be removed first from the debris at Ground Zero. However, barges of steel that were being unloaded in February and March at the Jersey City and Newark salvage yards were found to have pieces from the higher floors.

D.5 Conclusions and Future Work

The ongoing volunteer effort of the SEAoNY engineers is securing WTC steel pieces that will provide physical evidence for studies on WTC building performance. As of March 15, 2002, seventeen engineers, visiting four salvage yards, have identified approximately 150 pieces. Pieces have been identified that are from WTC 1, 2, 5, and 7. Documentary photographs and videos have been taken and coupons collected.

Future studies are expected based on the pieces and data collected. Coupons have been collected for metallurgical tests to determine the temperatures to which they were subjected and their steel characteristics. The National Institute of Standards and Technology (NIST) is currently conducting environmental tests, abating asbestos as necessary, and shipping available pieces to its Gaithersburg, MD, facility for storage and further study. As of May 2002, a total of 41 steel pieces had been shipped to NIST.

D.6 References

Gillespie, A.K. 1999. *Twin Towers, 1999. The Life of New York City's World Trade Center.* Rutgers University Press. New Brunswick, NJ. ISBN 0-8135-2742-2.

Steel Data Collection Spreadsheet

SEAoNY Summary of Identified WTC Steel Pieces at Salvage Yards
as of March 15, 2002

Note: As of May 2002, of the 156 steel pieces listed in the spreadsheet, 41 are at the National Institute of Standards, 19 were discarded after coupons were taken, 45 are at the salvage yards, and the rest either were discarded after they were documented or were accidentally processed in the salvage operation before or after being documented.

	Yard	Trip Date	Note Taker	Piece ID Mark	d	t_w	b_f	t_{tf}	t_{bf}	t_s	~L	Remarks (description, photos/videos, coupons)
1	CM	10/10/01	-	01	See Remarks							One of 10 full-size pieces of exterior and interior columns marked during ASCE visits. These pieces were accidentially processed in salvage yard operations before being documented
2	CM	10/10/01	-	02	13-1/2"	2-1/2"	9"	7/8"	7/8"	15/16"	36'	One full-length perimeter column w/2 99" long spandrel plates suggesting use in sky lobby location. Piece painted with markings "ASTANEH 2 ASCE". Piece was in Astaneh's pile and was measured by David Sharp of SEAoNY on 3/11/02.
3	CM	10/10/01	-	03	13-1/2"	1-7/8"	10-1/2"	5/8"	5/8"	~3/4"	17'	One perimeter column w/portion of a spandrel plate. Stamped markings "L2042 1 144 45". Piece painted with markings "ASTANEH 3 ASCE". Piece was in Astaneh's pile and was measured by David Sharp of SEAoNY on 3/11/02.
4	CM	10/10/01	-	04	See Remarks							Same as Piece 01, above.
5	CM	10/10/01	-	05	See Remarks							Same as Piece 01, above.
6	CM	10/10/01	-	06	See Remarks							Same as Piece 01, above.
7	CM	10/10/01	-	07	See Remarks							Same as Piece 01, above.
8	CM	10/10/01	-	08	See Remarks							Same as Piece 01, above.
9	CM	10/10/01	-	09	See Remarks							Same as Piece 01, above
10	CM	10/10/01	-	10	See Remarks							Same as Piece 01, above.
11	CM	10/10/01	-	11	See Remarks							Fire-damaged piece of wide flange. Otherwise, same as Piece 01, above.
12	CM	12/19/01	Gilsanz	AA	11"	1-3/8"	11-1/4"	9/16"	n/a	1-1/4"		(Photo:DKoutsoubis:1/30/02:#43-48) From WTC 1 or 2 with fire damage &/or floor location. Depth measurement does not include portion of web beyond bottom flange.
13	CM	12/19/01	Gilsanz	BB	11"	n/a	11-3/8"	7/16"	n/a	9/16"		(Photo:DKoutsoubis:1/30/02:#49-52). From WTC 1 or 2 with fire damage &/or floor location. Depth measurement does not include portion of web beyond bottom flange.
14	CM	12/19/01	Gilsanz	CC	10-7/8"	1-1/6"	11-1/2"	7/16"	3/8"	9/16"		(Photo:DKoutsoubis:1/30/02:#53-58) From WTC 1 or 2 with fire damage &/or floor location. Depth measurement does not include portion of web beyond bottom flange

	Yard	Trip Date	Note Taker	Piece ID Mark	d	t_w	b_f	t_{ff}	t_{bf}	t_s	~L	Remarks (description, photos/videos, coupons)
15	CM	12/19/01	Gilsanz	DD	13-7/8"	1-1/8"	11-1/4"	1/4"	3/8"	1/2"		(Photo:DKoutsoubis:1/30/02:#59-62) From WTC 1 or 2 with fire damage &/or floor location.
16	CM	12/19/01	Gilsanz	EE	n/a	7/16"	n/a	~1/4"	~1/4"	7/16"		(Photo.DKoutsoubis:1/30/02:#74-82) From WTC 1 or 2 with fire damage &/or floor location.
17	CM	12/19/01	Sharp	FF	13-1/2"	1-9/16"	10-5/8"	~3/8"	7/16"	1-1/4"	25'	Piece marked 12/19/01, measured 1/30/02. (Photo:DKoutsoubis:1/30/02:#83-88) Single bow-shaped badly burned perimeter column. "Left" column from interior perspective determined by bolt splice. Primer gone
18	CM	12/19/01	Sharp	GG	See Remarks							Piece marked 12/19/01, measured 1/30/02. Sample of a bolt splice taken from a perimeter column from sky-lobby floor as indicated by two large spandrel plates. Piece was selected for intact bolt splice only. Photo:DKoutsoubis:1/30/02:#89-97.
19	CM	12/19/01	Sharp	HH	12"	1/2"	12-1/4"	3/4"	3/4"	n/a	14'	Piece marked 12/19/01, measured 1/30/02. (Photo.DKoutsoubis:1/30/02:#98-102) Core column section with bottom and splice intact, brittle failure in midpoint.
20	CM	12/19/01	Gilsanz / Sharp	A or W14A	16"		15-1/2"	1-3/16"				WTC#7 W14 chosen for seat section response. Seat measurements taken. Seat is 8" X 7-1/2" X 3/8" thick. Stiffener is 9-5/8" X 5-1/4" X 3/8" thick. Bolt holes are 15/16". Photo by DKoutsoubis:1/30/02:#68-73.
21	CM	12/19/01	Gilsanz / Sharp	B or W14B	See Remarks							WTC#7 W14 chosen due to seat section response. Seat measurments taken Seat is 7-1/2" X 7-1/4" X 3/8" thick. Photo by DKoutsoubis: 1/30/02:#63-67.
22	CM	1/0802	Bonilla	C10	11-1/2"	3/16"	14"	3/8"	5/16"	3/8"		Chosen due to floor location. Perimeter column from WTC 1 or 2. Piece marked "98-85 L2337 461". DSharp photo.
23	CM	1/8/02	Bonilla	C11	11-1/2"	n/a	14"	1/4"	1/4"	3/8"		Chosen due to floor location. Perimeter column from WTC 1 or 2. DSharp photo.
24	CM	1/21/02	Koutsoubis	C12a	14-3/4"	5/8"	14-3/4"	1"				Chosen due to connection type. WTC#7 W14 tree column-column piece. (Photo.DKoutsoubis:1/21/02:#40-45).
	CM	1/21/02	Koutsoubis	C12b	23-5/8"	1/2"	7"	5/8"				WTC#7 W14 tree column-beam piece. Beam arm length is 4' 5-1/8" Attached to C12a. (Photo:DKoutsoubis:1/21/02.#40-45).
25	CM	1/23/02	Sharp	C13a	13-3/4"	1/4"	13-1/2"	1/4"	1/4"	3/8"	~30 ft	Chosen due to floor location. Markings on Steel: "321 B200 92 80 3T <569>" (Photo.DKoutsoubis:1/25/02:#15-19).
	CM	1/23/02	Sharp	C13b	7-5/8"	1/4"	12-1/2"	5/16"	1/4"	3/8"		Box column attached to C-13a. Possibly indicates floor/corner of WTC 1 or 2. (Photo:DKoutsoubis:1/25/02:#20-25).
26	CM	1/23/02	Sharp	C14a	13-1/2"	1/4"	13-1/4"	5/16"	5/16"	3/8"		Chosen due to floor location. Perimeter column from WTC 1 or 2. (Photo:DKoutsoubis:1/25/02:#10-14) Markings "3T <579> B300 85-87".

	Yard	Trip Date	Note Taker	Piece ID Mark	d	t_w	b_f	t_{if}	t_{of}	t_s	~L	Remarks (description, photos/videos, coupons)
	CM	1/24/02	Sharp	C14b	n/a	5/16"	5-7/8"	n/a	n/a	n/a		Small portion of a box section, attached to C14a. Small 'Tin' box too.
27	CM	1/23/02	Sharp	C15	13-3/8"	1/4"	13-1/4"	1/4"	~3/8"	3/8"		Perimeter Column from WTC 1 or 2, no clearly evident markings. Chosen due to floor location.(Photo:DKoutsoubis:1/25/02:#26-30).
28	CM	1/23/02	Sharp	C16	13-3/4"	1/4"	13" +	1/4"	1/4"	3/8"	~15ft	Marking on t+M4Gop of diaphragm plate (or top of column?) "75 1 203" Chosen due to floor location. (Photo:DKoutsoubis:1/25/02:#90-94).
29	CM	1/23/02	Sharp	C17	13-1/2"	1/4"	13-1/2"	1/4"	3/16"	3/8"		Two perimeter columns from WTC 2? Chosen due to floor location. Markings: "92-95" "248B 224" (Photo:DKoutsoubis:1/25/02:#39-42).
30	CM	1/23/02	Sharp	C18	13-3/4"	1/4"	13-3/6"	1/4"	1/4"	3/8"		Nut and washer found in box, as well as a letter from AON "Two World Trade Center". (Photo:DKoutsoubis:1/25/02:#31-37) Markings: "+3/16"
31	CM	1/23/02	Sharp	C19	13-1/2"	1/4"	12-3/4"	1/4"	1/4"	3/8"	~15ft	Single perimeter column from WTC 1 or 2. Chosen due to floor location. Fire damage. (Photo:DKoutsoubis:43-48).
32	CM	1/23/02	Sharp	C20	13-1/4"	1/4"	13-3/8"	5/16"	1/4"	3/8"		Three perimeter columns together, chosen due to floor location and some evidence of fire damage on connection. (Photo:DKoutsoubis:1/25/02:#51-55) Markings "4T <557> 91-94" Floor connection upside down?
33	CM	1/23/02	Bonilla	C21	13-1/2"	1/4"	13-1/2"	1/4"	1/4"	3/8"		Perimeter Column from WTC 1 or 2. Chosen due to floor location. (Photo:DKoutsoubis:1/25/02:#65-70).
34	CM	1/23/02	Bonilla	C22	13-1/2"	1/4"	13-1/4"	1/4"	1/4"	3/8"		Piece is marked: "PONYA 4T <69> A?? 93 - ??. Chosen due to floor location and moderate fire damage. Stamped "3146 96-93" (Photo:DKoutsoubis:1/25/02:#124-127).
35	CM	1/23/02	Bonilla	C23	13-1/2"	9/32"	13-3/8"	5/16"	1/4"	3/8"		Perimeter column section flared apart, no fire, column ends peeled apart. Chosen due to floor location.
36	CM	1/25/02	Bonilla	C24	13-1/2"	5/8"	13"	5/16"	1/4"	5/8"		(Photo:DKoutsoubis:1/25/02:#83-86) Chosen due to availability of column to column bolts being intact. 9 of 12 3/4" bolts available. Depth of spandrel 8' 3". Piece marked "77-78 203".
37	CM	1/25/02	Bonilla	C25	13-1/2"	1/4"+	13"	5/16"	1/4"	3/8"	~16 ft	(Photo:DKoutsoubis:1/25/02:#83-86) Chosen due to floor location. No clearly evident fire damage, single perimeter column w/2 spandrel plates. Crayon markings: "A206 <69> 89-92"
38	CM	1/25/02	Sharp	C26	27-1/4"	1/2"	10-1/4"	3/4"	3/4"			(Photo:DKoutsoubis:1/25/02:#56-64) Chosen due member type, 2 1" gusset plates w/3 connecting W sections. Main section has utility cut-outs. RB&W ASTM A490 bolts.
39	CM	1/25/02	Sharp	C27	12-1/4"	3/8"	10"	9/16"	9/16"		~14 ft	(Photo:DKoutsoubis:1/25/02:#71-77) Chosen due member type, W12 bow-shaped.

	Yard	Trip Date	Note Taker	Piece ID Mark	d	t_w	b_f	t_{tf}	t_{bf}	t_s	~L	Remarks (description, photos/videos, coupons)
40	CM	1/25/02	Bonilla	C28a	13-1/2	5/16"	13"	5/16"	n/a	3/8"		{Photo:DKoutsoubis:1/25/02:#136-139} Chosen due to floor location.
	CM	1/26/02	Bonilla	C28b	7-3/8"	3/8"	12-1/4"	5/16"	n/a	3/8"		Attached to C28a, square column w/rectangular column. Intact seat, 3 or 4 bolts present.
41	CM	1/25/02	Sharp	C29	14-3/4"	1-1/8"	12-1/2"	1-3/4"	1-3/4"			{Photo:DKoutsoubis:1/25/02:#101-107} Chosen due to member type and weight, W14 'C'-shaped
42	CM	1/25/02	Sharp	C30	16-1/2"	1-1/8"	15-7/8"	1-7/8"	1-7/8"			{Photo.DKoutsoubis:1/25/02.#108-111} Chosen due to member type and weight. W14 'C'-shaped.
43	CM	1/25/02	Koutsoubis	C31a	15-3/8"	13/16"	15-1/2"	1-1/4"	1-1/4"		-24 ft	{Photo:DKoutsoubis:1/25/02:#118-123} W14 Tree. Chosen due to piece type
	CM	1/25/02	Koutsoubis	C31b	24"	1/2"	7"	5/8"	5/8"			Matching beam attached to C31a column tree.
44	CM	1/25/02	Koutsoubis	C32	14"	1-3/8"	11-1/4"	7/16"	7/16"	11/16"		{Photo:DKoutsoubis:1/25/02:#128-131} Selected by Steficek due to fire damage.
45	CM	1/25/02	Koutsoubis	C33	13-3/4"	1/2"	n/a	1/4"	n/a	7/16"		Selected by Steficek.Chosen due to piece type/original floor location. Photo by DKoutsoubis:1/25/02:#132-135
46	CM	1/25/02	Koutsoubis	C34	14"	1"	12"	3/8"	3/8"	1/2"		Selected by Steficek. Chosen due to piece type/original floor location. Photo by DKoutsoubis:1/25/02.#140-143.
47	CM	1/25/02	Koutsoubis	C35	14"	7/8"	12-1/2"	1-1/2"	1-1/2"		-36 ft.	{Photo:DKoutsoubis:1/25/02:#144-146} Selected by Bonilla. W section column w/ slot connections.
48	CM	1/30/02	Sharp	C40	13-1/2"	5/16"	13"	1/4"	1/4"	3/8"	~20 ft	{Photo:DKoutsoubis:1/30/02:#6-12} 2 joined perimeter columns chosen due to floor location. Bent in middle. Marking: '98-101 <89> 51 101'.
49	CM	1/30/02	Sharp	C41	13-1/2"	3/8"	13-1/8"	1/4"	n/a	3/8"	~20 ft	{Photo.DKoutsoubis:1/30/02.#13-19} 1 perimeter column with 2 areas of fire damage. Chosen due to floor location.
50	CM	1/30/02	Sharp	C42a	14-5/8"		14-5/8"	1"				{Photo:DKoutsoubis:1/30/02:#20-26} Chosen to member type, column tree W14 w/2 floor connections.
	CM	1/30/02	Sharp	C42b	23-7/8"		7"	9/16"				Beam attached to C42b column.

	Yard	Trip Date	Note Taker	Piece ID Mark	d	t_w	b_f	t_{tf}	t_{bf}	t_s	~L	Remarks (description, photos/videos, coupons)
51	CM	1/30/02	Sharp	C43	13"	3/8"	13-1/2"	7/16"	5/16"	3/8"	~20 ft	(Photo:DKoutsoubis:1/30/02:#27-31) Chosen due to floor location. Fire damaged mangled end
52	CM	1/30/02	Sharp	C44	12-1/8"		10"	5/8"			~13 ft	(Photo:DKoutsoubis:1/30/02:#32-35) W12 X58 Core column? Markings: "<583> 59(S)".
53	CM	1/30/02	Sharp	C45	11-3/4"		12"	5/8"	3/8"		~15 ft	(Photo:DKoutsoubis:1/30/02:#36-42) W12 x65 Core column? Markings. "<583> 16(S2)".
54	CM	2/4/02	Sharp	C46	13-1/2"	5/8"	12-5/8"	1/4"	3/8"	9/16"		(Photo DSharp) 3 column section from tower 2, dimensions taken from 'right' column. Chosen due to location just below impact area Tower B. Markings "PONYA 81 <586> B157-68-71" Moderate fire damage.
55	CM	2/4/02	Sharp	C47	13-1/2"	1/4"	13"	1/4"	1/4"	3/8"	~20 ft	(Photo DSharp) 3 column section. Primer burned off. Rust. Webs split.
56	CM	2/4/02	Sharp	C48	13-1/2"	1/4"	13-1/4"	1/4"	1/4"	3/8"		(Photo DSharp) 2 perimeter columns from 1 or 2, fire damage on bottom
57	CM	2/4/02	Sharp	C49	13-1/2"	1/4"	12-3/4"	1/4"	1/4"	3/8"	~12 ft	(Photo DSharp) 1 perimeter column w/fire damage.
58	CM	2/4/02	Sharp	C50	13-1/2"	3/8"	13-1/8"	1/4"	1/4"	3/8"		(Photo DSharp) Folded in two. Markings "A103-87" Piece stamped "L9863" "122-36 100".
59	CM	2/4/02	Sharp	C51	13-1/2"	3/8"	13"	1/4"	1/4"	3/8"		(Photo DSharp) 2 perimeter columns w/90 deg bend on one & 1/2 missing on the other.
60	CM	2/4/02	Sharp	C52	13-1/4"	5/16"	13-1/4"	1/4"	1/4"	3/8"	~15 ft	(Photo DSharp) perimeter column, buckled at spandrel where there is fire damage Unique seat configuration detail.
61	CM	2/4/02	Bonilla	C53	n/a	n/a	n/a	n/a	n/a	n/a		Listed dimensions not applicable.Floor truss with L4" X 5-1/2" Seat. & L2x1-1/2 x 1/4. Bolt= 1-1/8" nom dia. Photo DSharp.
62	CM	2/6/02	Sharp	C54	13-1/2"	1/4"	13-1/2"	1/4"	1/4"	none	~4 ft	(Photo DSharp) 1 3 ft piece of a perimeter column w/one plate extending ~15 ft.
63	CM	2/6/02	Sharp	C55	13-1/2"	5/16"	13-1/2"	5/16"	5/16"	none	~8 ft	1 perimeter column section. DSharp photo.
64	CM	2/13/02	Bonilla	C60	10-1/2"	1/2"	12"	3/4"				W Section 2 extreme bends. 'S'-shaped.

	Yard	Trip Date	Note Taker	Piece ID Mark	d	t_w	b_f	t_{ff}	t_{bf}	t_s	~L	Remarks (description, photos/videos, coupons)
65	CM	2/13/02	Bonilla	C61	10-3/4"	1/2"	12-1/4"	3/4"				W Section. Markings "150 (S) <89> 13 152W093 367". DSharp photo.
66	CM	2/13/02	Bonilla	C62	11"	1/2"	12-1/4"	5/8"				W Section. Markings "224(S) <48> 7409 351 F450" DSharp photo.
67	CM	2/13/02	Bonilla	C63	14-1/2"	3/8"	13"	1/4"	1/4"	3/8"		Perimeter column markings "97-100" Significant fire damage. 4 fasteners recovered from 'box'. 3 nuts w/bolt piece. 1 nut with threads stripped. DSharp photo.
68	CM	2/13/02	Bonilla	C64	11-1/2"+	1/4"	n/a	1/4"	n/a	3/8"	~12 ft	Perimeter column with only 3 sides remaining. DSharp photo.
69	CM	2/13/02	Bonilla	C65	10-3/4"	1"	12-1/2"	1-1/2"				W Section. 'C'-shaped. Concave side w/slotted clip. Convex side has connection plate. DSharp photo.
70	CM	2/19/02	Massa	C66a	13"	3/4"	13-1/2"	1-1/4"	n/a	n/a		Column Tree -column piece. DSharp photo.
	CM	2/19/02	Massa	C66b	~14-1/2"	5/8"	14-3/4"	1"	n/a	n/a		Column tree -beam piece attached to C66a. DSharp photo.
71	CM	2/19/02	Massa	C67	~11"+	1/4"	~13-1/2"	n/a	1/4"	3/8"		Single perimeter column from WTC 1 or 2 w/spandrel plate. DSharp photo.
72	CM	2/19/02	Massa	C68	13-1/2"	7/16"	13"	1/4"	1/4"	3/8"	~16 ft	4 bolts intact at col-col bearing plate.
73	CM	2/19/02	Massa	C69	16"	3/4"	12"	1-1/2"	n/a	n/a	~7 ft	Double 'T'-section bolted at web. Cracked and missing washers. DSharp photo.
74	CM	2/19/02	Massa	C70	11"	1"	12-1/2"	1-3/4"	n/a	n/a	~10 ft	S'-shaped W-Section w/2 seats. DSharp photo.
75	CM	2/19/02	Massa	C71	11"	1"	12-3/4"	1-3/4"	n/a	n/a	~14 ft	C'-shaped W-Section. DSharp photo.
76	CM	2/19/02	Massa	C72a	12"	3/4"	14-1/2"	1"	n/a	n/a		Column tree w/2 floor connections. Column piece markings "[6] 87-259". DSharp photo.
	CM	2/19/02	Massa	C72b	21-1/2"	~1/2"	~7"	5/8"	n/a	n/a		Column tree w/2 floor connections. Beam piece attached to C72a. DSharp photo.

	Yard	Trip Date	Note Taker	Piece ID Mark	d	t_w	b_f	t_{tf}	t_{bf}	t_s	~L	Remarks (description, photos/videos, coupons)
77	CM	2/19/02	Massa	C73	13-1/4"	3/8"	13-1/4"	1/4"	1/4"	3/8"	~15 ft	Perimeter column from WTC 1 or 2 w/spandrel plate DSharp photo.
78	CM	2/19/02	Massa	C74a	12-1/2"	3/4"	14-1/2"	1"	n/a	n/a	~10 ft	Column tree --- column piece attached to C72b. DSharp photo.
	CM	2/19/02	Massa	C74b	~22-1/2"	7/16"	7"	1/2"	n/a	n/a		Column tree --- beam piece attached to C74a.
79	CM	2/19/02	Massa	C75	13-1/2"	7/8"	12-1/4"	5/16"	5/16"	3/8"	~15 ft	One perimeter column for WTC 1 or 2 w/spandrel plate. DSharp photo.
80	CM	2/19/02	Massa	C76	18-1/4"	5/8"	12"	2" (1"X2)	n/a	n/a	~13 ft	W-Section w/top and bottom plates splayed apart. Interm Welds. DSharp photo
81	CM	2/19/02	Massa	C77	13-1/2"	1/4"	13-1/2"	1/4"	1/4"	3/8"		2 perimeter columns pieces from WTC 1 or 2. Splice at spandrel DSharp photo.
82	CM	2/19/02	Massa	C78a	12-3/4"	1-3/8"	16"	2-1/8"	n/a	n/a	~14 ft	Column tree, one floor --- column piece. DSharp photo.
	CM	2/19/02	Massa	C78b	22"	7/16"	7"	5/8"	n/a	n/a		Column tree, one floor --- beam piece attached to C78a. DSharp photo.
83	CM	2/19/02	Massa	C79	4"	3/8"	16"	3/4"	n/a	n/a	~14 ft	Rectangular column, core style from 1 or 2 WTC. DSharp photo."
84	CM	2/25/02	Sharp	C80		15"	7/8"	15-1/2"	1-3/8"	n/a	n/a	Perimeter column marked "603A 92-95 <51>".
85	CM	2/19/02	Massa	C81	~31-1/2"	7/8"	16-1/2"	1-5/8"	1-5/8"	n/a	12'	Photos AMassa and DSharp. Beam section painted "SAVE FEMA G". Flame cut on one end. ductile buckling on the other end.
86	CM	3/11/02	Sharp	C82	? Folded	7/16"	10"	11/16"	2"	n/a	16'	Beam section painted "SAVE FEMA H". Mechanical cut-outs, built-up bottom flange. ductile web buckling. Photo DSharp.
87	CM	3/11/02	Sharp	C83	13"	1-1/2"	34"	1-1/2"	1-1/2"	n/a	23'	Core column box section originally chosen by Astaneh, and placed in his pile. Document by David Sharp of SEAoNY for information purposes.
88	CM	3/11/02	Sharp	C84	13-1/2"	2-5/8"	9-5/8"	7/8"	7/8"	1-1/4"	36'	Piece originally selected by Astaneh and in his pile. Single full length perimeter column with 3 spandrel plates. Bolt splice suggests outer column of tree. Documented by David Sharp of SEAoNY for information purposes.

	Yard	Trip Date	Note Taker	Piece ID Mark	d	t_w	b_f	t_{tf}	t_{bf}	t_s	~L	Remarks (description, photos/videos, coupons)
89	CM	3/11/02	Sharp	C85a	12-3/4"	1-3/16"	16"	1-3/4"	1-3/4"	n/a		Piece originally selected by Astaneh and in his pile. Column tree with 9'+ floor separation. Full width welded seat. 2 floors+ in length. Documented by David Sharp of SEAoNY for information purposes. Dimensions for column section.
	CM	3/11/02	Sharp	C85b	15"	7/16"	~7"	3/4"	3/4"	n/a		Piece originally selected by Astaneh and in his pile. Beam section from C85a column tree. Documented by David Sharp of SEAoNY for information purposes.
90	CM	3/11/02	Sharp	C86	n/a24"+	1-1/2"	13"	1-1/2"	1-1/2"	n/a	3'	Small folded box section from core. Torch cut, originally chosen by Astaneh and in his pile. Documented by David Sharp of SEAoNY for information purposes.
91	CM	3/11/02	Sharp	C87	~22"	7/16"	10"	1/2"	2"	n/a	25'	Beam section with viscous damper attached. Mechanical cut-outs and built-up bottom flange.
92	CM	3/11/02	Sharp	C88	12"	1-1/2"	16"	1-1/2"	1-1/2"	n/a		Core box column w/two straps and seat, painted "SAVE PA". Also has markings "<55?>" Completely splayed apart above seat.
93	CM	3/11/02	Sharp	C89	13-1/2"	1-13/16"	10-1/4"	5/8"	5/8"	1-3/8"	36'	Two badly burned perimeter columns, full length. Spandrel plates flame cut. Markings stamped on piece. "1.3 144 146 50 B216 15 12" Piece originally chosen by Astaneh and in his pile. Documented by David Sharp of SEAoNY for information purposes only.
94	CM	3/11/02	Sharp	C90	8-3/4"	3-1/4"	37"	3-1/4"	3-1/4"	n/a	36'	Core column box section originally chosen by Astaneh, and placed in his pile. Documented by David Sharp of SEAoNY for information purposes. Piece is 'S'-shaped and has cracks running along the welds in buckles areas.
95	CM	3/14/02	Sharp	C91	10-5/8"	3/4"	4-1/8"	1-3/8"	1-3/8"	n/a	14'	Beam section with built-up flanges and two seats. Probable core section floor truss connection. Splice plates on both ends.
96	CM	3/14/02	Sharp	C92	13-1/2"	~1/2"	13"	1/4"	1/4"	3/8"	15'	Single perimeter column with 2 seats. 'Outside' column from 'right' via view from building interior. (Bolt splice on right).
97	CM	3/14/02	Sharp	C93	13-1/2"	5/16"	13-1/4"	1/4"	1/4"	3/8"	8'	One portion of a light construction perimeter column.
98	KB	11/20/01	Gilsanz/ Steficek		See Remarks							Portion of spandrel plate and two bolts from WTC 1 or 2. Coupon A. Photos: A-1(coupon cut location), A-2 (coupon side and top view), A-3(coupon bottom). Steficek video.
99	KB	11/20/01	Gilsanz/ Steficek		See Remarks							Coupon B of web and flange sections from perimeter column from WTC 1 or 2. Photos: B-1(coupon cut location), B-2 (coupon front), B-3(coupon perpendicular view). Steficek video
100	KB	11/20/01	Gilsanz/ Steficek		See Remarks							Coupon C of web and flange sections from perimeter column from WTC 1 or 2. Photos: C-1(coupon cut location), C-2 (coupon full view), C-3 (coupon side view). Steficek video
101	KB	12/19/01	Gilsanz	K-1	n/a	7/16"	n/a	1/4"	1/4"	3/8"		Chosen due to floor location. Piece marked "98-98".

	Yard	Trip Date	Note Taker	Piece ID Mark	d	t_w	b_f	t_{tf}	t_{bf}	t_s	~L	Remarks (description, photos/videos, coupons)
102	KB	12/19/01	Gilsanz	K-2	13-3/4"	0.92"	30"	0.92"	n/a	n/a		Chosen due to fire damage, floor location
103	KB	12/20/01	Chuliver	K10	12"	9/16"	13"	1/2"	1/4"	1/2"		Chosen due to fire damage. Photo 1-byABonilla. Coupon taken and brought to GMS. Coupon photo by AMassa.
104	KB	12/20/01	Chuliver	K11	14"	1-1/8"	11-5/8"	1/2"	n/a	1/2"		Chosen due to fire damage.Photo 2-byABonilla. Coupon taken and brought to GMS. Coupon photo by AMassa.
105	KB	12/20/01	Chuliver	K12	13-3/4"	7/16"	13"	5/8"	n/a	7/16"		Chosen due to floor location. Photo 3-byABonilla. Coupon taken and brought to GMS. Coupon photo by AMassa.
106	KB	12/20/01	Chuliver	K13	13-11/16"	1/4"	13-1/2"	1/4"	9/16"	3/8"		Chosen due to floor location and fire damage. Photo 5-byABonilla.Coupon taken and brought to GMS. Coupon photo by AMassa.
107	KB	12/20/01	Chuliver	K14	13-1/2"	1/4"	13-3/16"	3/8"	1/2"	3/8"		Chosen due to floor location and fire damage. (Photo.DKoutsoubis.12/27/02.#32-41). Photos 6-7-byABonilla. Stencil mark: floors 91-94. Coupon taken and brought to GMS. Coupon photo by AMassa.
108	KB	12/27/01	Chuliver	K15a	13-1/4"	1/4"	13-1/2"	5/16"	?	3/8"		Chosen due to floor location. Photo 4-by DSharp. Coupon taken and brought to GMS. Coupon photo by AMassa.
	KB	12/27/01	Chuliver	K15b	7-3/8"	3/8"	12-1/4"	3/8"	1/4"			Chosen due to floor location. Photo 5-by DSharp. Rectangular piece attached to K15a.
109	KB	1/19/02	Koutsoubis	K16	13-7/8"	1-3/8" to 1-3/4"	11"	1/2"	3/8"	1-1/4"-1-5/8"		Chosen due to unique Thickness variations, due to corrosion or fire? Video Sharp Photo.DKoutsoubis.1/19/02:#1-13.
110	KB	1/19/02	Koutsoubis	K17	13-5/8"	1-1/2"	10-7/8"	1/2"	5/8"	13/16"		Chosen due to fire damage. Video by DSharp. Photos by Dkoutsoubis 1/16/02:#13-16 and 1/19/02:#14-24.
111	KB	12/27/01	Chuliver	K18	11-1/4"	3/8"	13-1/4"	1/4"	3/8"	1/4"		Chosen due to floor location. Photos by DKoutsoubis.12/27/02.#14-22 and video.12/27/01:2m6s. Coupon taken and brought to GMS. Coupon photo by AMassa
112	KB	12/27/01	Chuliver	K19	14"	7/8"	12-1/4"	5/16"	n/a	3/4"		Chosen due to fire damage. Photos by DKoutsoubis:12/27/01:#23-27, 30-31 and video:12/27/01:1m24s.Coupon taken and brought to GMS. Coupon photo by AMassa.
113	KB	12/27/01	Koutsoubis	K20	13-1/2"	1/4+"	13	1/4"	1/4"	3/8+"		Chosen due to floor location. Photos by DKoutsoubis.12/19/01:#41-48 and 12/27/01:#1-11, and video.2m3s
114	KB	1/18/02	Sharp	K40	11"	1/4"	13"	1/4"	1/4"	3/8"		Chosen due to floor location. Photos 58-60 (Hoy)? Marking on piece is 92-95. Also marked 252.

	Yard	Trip Date	Note Taker	Piece ID Mark	d	t_w	b_f	t_{tf}	t_{bf}	t_s	~L	Remarks (description, photos/videos, coupons)
115	KB	1/18/02	Sharp	K41	13-3/8"	3/8"	13-1/2"	1/4"	1/4"	3/8"		Chosen due to floor location Photos 57-58 (Hoy). Marking on piece is "L9901 120".
116	KB	1/19/02	Sharp	K50	See Remarks							Sample of washer failure. Piece photos by DKoutsoubis:1/30/02:41-5. Piece cut into 3 sections and brought to GMS offices.
117	NW	11/16/01 to 1/18/02	DePaola/ NIST	NIST N-1	13-1/2"	1/2"	13"	3/8"	1/2"	1/2"	3' 8"	Perimeter column. Photo N-1 by NIST.
118	NW	11/16/01 to 1/18/02	DePaola/ NIST	NIST N-2	See Remarks							Piece is comprised of the majority of the pieces which make up a floor truss section from WTC 1 or 2 Dimensions not applicable. Photo N-2 by NIST.
119	NW	11/16/01 to 1/18/02	DePaola/ NIST	NIST N-3	13-1/2"	5/16"	9-1/2"	1/2"			87"	Perimeter column. Photo N-3 by NIST.
120	NW	11/16/01 to 1/18/02	DePaola/ NIST	NIST N-4	13"	3/8"	13"	3/8"	3/8"	9/16"	16'	Perimeter column. Photo N-4 by NIST.
121	NW	11/16/01 to 1/18/02	DePaola/ NIST	NIST N-5	1-3/8"	See Remarks						4' 4" X 11" section of a bolted connection area (spandrel splice) from a perimeter column. Photo N-5 by NIST.
122	NW	11/16/01 to 1/18/02	DePaola/ NIST	NIST N-6	13-1/4"	3/8"	14"	1/2"	1/2"	9/16"	4' 6"	Perimeter column. Photo N-6 by NIST
123	NW	2/8/02	Koutsoubis	M2	13-1/4"	5/16"	13-1/4"	1/4"	3/8"	3/8"		(Photo:DKoutsoubis:2/8/02:13,15-21) Evidence of burning.
124	NW	2/8/02	Koutsoubis	M3	13-3/4"	5/16"	13-1/2"	1/4"	1/4"	5/16"		(Photo:DKoutsoubis.2/8/02:23-28)(Photo:DKoutsoubis:2/14/02:17-21) Evidence of burning.
125	NW	2/8/02	Hoy	M4	13-1/4"	1/4"	13-1/4"	1/4"	1/4"	3/8"		(Photo:DKoutsoubis:2/8/02:30-34) "Mushed" end
126	NW	2/8/02	Koutsoubis	M5	14"	1/4"	13-1/2"?	1/4"	1/4"	3/8"		(Photo:DKoutsoubis:2/8/02:39-45) Thin spandrel. "d" dimension is approx
127	NW	2/8/02	Koutsoubis	M6	13-1/2"	1/4"	13-1/4"	1/4"	1/4"	3/8"		(Photo:DKoutsoubis:2/8/02:59-63) Thin spandrel.
128	NW	2/8/02	Hoy	M7	13-1/2"	5/16"	13-1/8"	1/4"	1/4"	3/8"		(Photo:DKoutsoubis:2/8/02:67-72) Evidence of burning

	Yard	Trip Date	Note Taker	Piece ID Mark	d	t_w	b_f	t_{tf}	t_{bf}	t_s	~L	Remarks (description, photos/videos, coupons)
129	NW	2/6/02	Koutsoubis	M8	13-1/2"	1/4"	13-1/4"	1/4"	1/4"	3/8"		(Photo:DKoutsoubis:2/8/02:79-86) Thin spandrel.
130	NW	2/8/02	Koutsoubis	M9	13-1/2"	1/4"	13-1/2"	1/4"	1/4"	3/8"		(Photo:DKoutsoubis:2/8/0281-84) Beat up. "tw" dimension is approx.
131	NW	2/8/02	Koutsoubis	M10	13-3/8"	5/16"	13-1/2"	1/4"	1/4"	3/8"		(Photo:DKoutsoubis:2/8/02:85-92) Burnt on inside.
132	NW	2/6/02	Koutsoubis	M11a	15-1/2"	3/4"	15-3/4"	1-1/2"				W14 Tree Column- column piece. Photos by DKoutsoubis:2/8/02:93-105.
	NW	2/9/02	Koutsoubis	M11b	23-5/8"	5/16"	7"	5/8"				Attached to M11a - beam piece of W14 tree column. Photos by DKoutsoubis:2/8/02:93-105.
133	NW	2/8/02	Koutsoubis	M12	~30"	~1/2"	10-1/2"	11/16"				Severely burnt & twisted wide-flange girder. Studs welded on the top flange. Photos by DKoutsoubis:2/8/02:106-114.
134	NW	2/25/02	Sharp	M13	13-1/2"	1/4"	13-1/2"	1/4"	1/4"	3/8"		Two perimeter columns folded in half. Stamped markings "06 92 95 2430". DSharp Photo.
135	NW	2/25/02	Sharp	M14	13-1/2"	1/4"	13-1/2"	5/16"	5/16"	3/8"		Spandrel markings "??? ST <83> ?? -99-102" Piece is stamped "99-102 9311 102" DSharp photo.
136	NW	2/25/02	Sharp	M15	13-1/2"	5/16"	13-1/2"	1/4"	1/4"	3/8"		Spandrel markings "PONYA A115-89-92 6T" Stamped markings: "89 92 L2816 115" and "L6973 17 125 36 55".
137	NW	3/1/02	Sharp	M16	13-1/2	9/32"	13-1/4"	1/4"	1/4"	3/8"		3 perimeter columns from WTC 1. Spandrel plate markings "PONYA A148 99-102 <67>" Piece stamped "102 99" Two small clips on damper.
138	NW	3/1/02	Sharp	M17	~22"	7/16"	12"	3/4"	1-1/8"	n/a	40'	Unique piece with portion of viscous damper attached, also straps and connections. Cut-outs for mechanical. Built-up flange. Marked "183 (9) <62>".
139	FK	12/6/01	Fahey/Rosa	A	36"	1/2"	10-1/2"	2-1/4"			19'-11"	Beam - Appeared heat affected. Flange coupon (A-1) & web coupon (A-2) marked 7"+/- from end of beam. Photo #'s 141, 142 & 475.
140	FK	12/6/01	Fahey/Rosa	B	36"	13/16"	12"	1-1/4"			4'-10"	Beam - Puncture. Web coupon (B-1) marked. Photo #'s 139, 140, 143 & 476.
141	FK	12/6/01	Fahey/Rosa	C	30-1/4"	1"	10"	2-1/2"			14'-5"	Beam - Appeared heat affected. Web coupon (C-1) marked. Photo #'s 135, 137, 138, 144 & 477.

	Yard	Trip Date	Note Taker	Piece ID Mark	d	t_w	b_f	t_{tf}	t_{bf}	t_s	~L	Remarks (description, photos/videos, coupons)
142	FK	12/6/01	Fahey/Rosa	D	21-1/4"	1"	17-7/8"	1-9/16"				Column - Puncture. Photo #'s 482 & 483.
143	FK	12/6/01	Fahey/Rosa	E	12-5/8"	3/4"	12-3/8"	1-1/8"				Column - Appeared heat affected. Web coupon (E-1) marked. Photo #'s 488 & 491.
144	FK	12/6/01	Fahey/Rosa	F	38"	3/4"	7"	1-3/4"				Beam - Appeared heat affected. Web coupon (F-1) marked. Photo #'s 490 & 491.
145	FK	12/19/01	Fahey/ McConnell	G	35-1/2"	7/8"	16-3/8"	1-9/16"				Beam. Coupon (G-1) marked on moment splice plate. Photo #'s 125, 128 & 129
146	FK	12/19/01	Fahey/ McConnell	H	21"+/-	1/2"	10"	3/4"			18'-9"	Beam. Web coupon (H-1) marked. Photo #'s 131, 132 & 133.
147	FK	12/19/01	Fahey/ McConnell	I	7-5/16"	3/4"	15-11/16"	1-1/16"				Brace - (2) WT's back to back - Appeared heat affected. Coupon (I-1) marked on gusset plate at end of brace. Photo #'s 145, 148, 149 & 150.
148	FK	12/19/01	Fahey/ McConnell	J	27"+/-	1/2"	10"+/-	1/2"				Beam. Web coupon (J-1) marked. Photo #'s 155, 156 & 157.
149	FK	12/19/01	Fahey/ McConnell	K	24-7/8"	3/4"	7"	1-1/2"				Beam. Web coupon (K-1) marked. Photo # 165.
150	GZ	~11/27/01	Eschenasy	-	See Remarks							Connection coupon recovered from WTC#5, 8th floor, and brought to GMS offices. Web tear-out at bolts. Coupon photo by AMassa. Sketch with dimensions and photo in this WTC BPS report, Fig. 4-22.
151	GZ	~11/27/01	Eschenasy	-	See Remarks							Connection coupon recovered from WTC#5, 7th floor, and brought to GMS offices. Web tear-out at bolts. Coupon photo by AMassa. Sketch with dimensions and photo in this WTC BPS report, Fig. 4-22.
152	GZ	~11/27/01	Eschenasy	-	See Remarks							Connection coupon recovered from WTC#5, 6th floor, and brought to GMS offices. Web tear-out at bolts. Coupon photo by AMassa. Sketch with dimensions and photo in this WTC BPS report, Fig. 4-22.
153	GZ	~11/27/01	Eschenasy	-	See Remarks							Connection coupon recovered from WTC#5, 6th floor, and brought to GMS offices. Web tear-out at bolts. Coupon photo by AMassa. Sketch with dimensions and photo in this WTC BPS report, Fig. 4-22.
154	GZ	~11/27/01	Eschenasy	-	See Remarks							Connection coupon recovered from WTC#5, 8th floor, and brought to GMS offices. Plate tear-out at bolts. Coupon photo by AMassa. Sketch with dimensions and photo in this WTC BPS report, Fig. 4-22.
155	GZ	~11/27/01	Eschenasy	-	See Remarks							Connection coupon recovered from WTC#5, 7th floor, and brought to GMS offices. Connection web-plate or splice-block shear. Coupon photo by AMassa. Sketch with dimensions and photo in this WTC BPS report, Fig. 4-22.

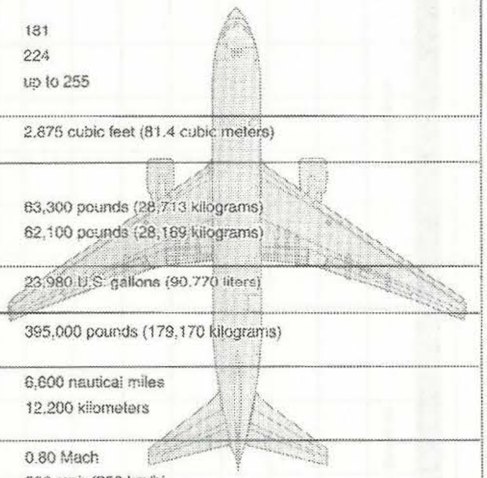
SEAoNY Summary of Identified WTC Steel Pieces at Salvage Yards as of March 15, 2002

	Yard	Trip Date	Note Taker	Piece ID Mark	d	t_w	b_f	t_{tf}	t_{bf}	t_s	~L	Remarks (description, photos/videos, coupons)
156	GZ	~11/27/01	Eschenasy	-	See Remarks							Connection coupon recovered from WTC#5, undetermined floor, and brought to GMS offices. Column buckling due to heat exposure. Coupon photo by AMasss. Sketch with dimensions and photo in this WTC BPS report, Fig. 4-22.

E *Aircraft Information*

Boeing 767-200ER

General Specifications



Passengers	
Typical 3-class configuration	181
Typical 2-class configuration	224
Typical 1-class configuration	up to 255
Cargo	2,875 cubic feet (81.4 cubic meters)
Engines' Maximum Thrust	
Pratt & Whitney PW4062	63,300 pounds (28,713 kilograms)
General Electric CF6-80C2B7F	62,100 pounds (28,169 kilograms)
Maximum Fuel Capacity	23,980 U.S. gallons (90,770 liters)
Maximum Takeoff Weight	395,000 pounds (179,170 kilograms)
Maximum Range	6,600 nautical miles
Typical city pairs: New York-Beijing	12,200 kilometers
Typical Cruise Speed at 35,000 feet	0.80 Mach 530 mph (850 km/h)
Basic Dimensions	
Wing Span	156 feet 1 inch (47.6 meters)
Overall Length	159 feet 2 inches (48.5 meters)
Tail Height	52 feet (15.8 meters)
Interior Cabin Width	15 feet 6 inches (4.7 meters)

Edward M. DePaola

F *Structural Engineers Emergency Response Plan*

It is recommended that local emergency response plans be developed for natural and manmade disaster events. The plans should define the roles and responsibilities of the parties involved, set up a system of credentialing, and define procedures for the participants. The plan should be flexible and comprehensive to allow for easy modification for differences encountered in each event. The following list, which was taken from the proposed SEAoNY "Structural Engineering Emergency Response Plan (SEERP)," is offered as a basis for the development of other similar plans:

1. Organizations willing to assist in natural or manmade disasters must immediately work with state and local governments to pre-establish a permanent relationship.
2. Issues relating to responsibilities and liabilities of individuals, firms and the organizations must be worked out in advance. These may include a process for the deputizing of volunteers or the enactment of "Good Samaritan" laws.
3. Response teams must be composed of pre-qualified volunteers and not drawn ad hoc from the organization's general membership.
4. There must be specific criteria to ensure that the volunteers are suitably qualified. Each volunteer should also be classified in accordance with their professional knowledge and physical abilities. As a minimum, they must be properly trained in emergency structural evaluations and perhaps urban search and rescue techniques.
5. A database must be created and maintained that contains all volunteer contact and other information.
6. There must be a chain of communication (a tree or pyramid system) for the contact of the volunteers in the event of an emergency.
7. Volunteers must have a specified set of equipment available at all times. Equipment must be tested and maintained regularly.
8. There must be specific, predetermined response locations where the volunteers are to report.

9. There must be a specific photo identification badge which is developed in conjunction with the local authorities. It is recommended that the individual's name, affiliation with the organization and qualifications as a "Structural Engineer" be clearly indicated. It is further recommended that these identifications have specific expiration dates. Periodic renewal will verify compliance with all requirements listed above.
10. The local authority should maintain command and control once the event occurs.
11. The volunteers must be kept actively involved and interested. When the actual disaster strikes, the organizers and the local government need to be assured that the volunteers will be ready, willing and able to help.
12. Volunteers should include experts in other specific disciplines as well. These may include architects, mechanical engineers, civil engineers specializing in underground utilities, and transportation engineers familiar with above- and below-ground transportation.
13. Volunteers for nontechnical assistance such as day-to-day coordination, communications, scheduling, and media relations are also important.
14. A database should be created that contains general information about selected buildings, including data concerning the structural systems, architectural layouts, principal contacts, fire alarm and suppression systems, drawings, and other useful information that would make for a more expedient emergency response.
15. Other Observations:
    - The magnitude of the event may require that plans be modified. Each situation must be evaluated separately. Contingency plans should be in place for all aspects of the response.
    - Situations change rapidly. Plans must be flexible and versatile and participants must have the ability to change with the situation.
    - Good communication equipment on the site is an absolute necessity. Although cell phones may eventually be workable, it must be assumed that normal communications at the event location are not properly functioning. The local authorities must provide high quality two-way radios for teams to keep in contact with each other and the local authorities.

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H Acronyms and Abbreviations

Acronyms

ACARS	Aircraft Communications Addressing and Reporting System
ACI	American Concrete Institute
AISC	American Institute of Steel Construction
APW	air-pressurized water
ASCE	American Society of Civil Engineers
ASMP	American Society of Media Photographers
ASTM	American Society for Testing and Materials
ATC	Applied Technology Council
BBC	British Broadcasting Corporation
BPM	built-up plate member
BPS	Building Performance Study
BRE	Building Research Establishment
BSI	British Standards Institute
CFD	Computational Fluid Dynamics
CIA	Central Intelligence Agency
CM	Claremont (salvage yard)
Con Ed	Consolidated Edison
CTBUH	Council on Tall Buildings in the Urban Habitat
DDC	Department of Design and Construction (NYC)
DEC	Department of Environmental Conservation
DoB	Department of Buildings (NYC)
DOD	Department of Defense
DOE	Department of Energy
EDT	Eastern Daylight Time
EDX	energy dispersive x-ray analysis
EEOC	Equal Employment Opportunity Commission
EPA	Environmental Protection Agency
FCC	Fire Command Center
FDNY	Fire Department of New York

FDS1	Fire Dynamics Simulator Version 1
FEM	finite element modeling
FEMA	Federal Emergency Management Agency
FK	Fresh Kills (salvage yard)
HSLA	high-strength low-alloy
HVAC	heating, ventilation, and air-conditioning
IRS	Internal Revenue Service
KB	Keasbey (salvage yard)
LDEO	Lamont-Doherty Earth Observatory (Columbia University)
LZA	LZA Technology/Thornton-Tomasetti
MTA	Metropolitan Transit Authority
NAIC	National Association of Insurance Commissioners
NBC	National Broadcasting Company
NBS	National Bureau of Standards
NCSEA	National Council of Structural Engineers Associations
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
NJ	New Jersey
NOAA	National Oceanic and Atmospheric Administration
NW	Newark (salvage yard)
NY	New York
NYBFU	NY Board of Fire Underwriters
NYC	New York City
NYPD	New York Police Department
OCC	Operations Control Center
OEM	Mayor's Office of Emergency Management (NYC)
PANYNJ	Port Authority of New York and New Jersey
PATH	Port Authority Trans-Hudson
SCBA	self-contained breathing apparatus
SEAoNY	Structural Engineers Association of New York
SEERP	Structural Engineering Emergency Response Plan
SEI	Structural Engineering Institute
SEI/ASCE	Structural Engineering Institute of the American Society of Civil Engineers
SFPE	Society of Fire Protection Engineers
SOM	Skidmore, Owings & Merrill
SSB	Salomon Smith Barney
STD	Standard
TMS	The Masonry Society
UL	Underwriters Laboratories
UPS	uninterruptible power supply
USC	United States Code
UTC	Coordinated Universal Time
WFC	World Financial Center
WTC	World Trade Center
Y/T	yield-to-tensile-strength ratio

Abbreviations

°C	degrees Celsius
°F	degrees Fahrenheit
cfm	cubic feet per minute
ft^2	square feet
gpm	gallons per minute
GW	gigawatt
Hz	hertz
in-k or kip-in	kip-inch
kips/bolt	kips per bolt
kg/m^2	kilograms per square meter
kJ/g	kilojoules per gram
km	kilometer
km/h	kilometers per hour
ksi	kips per square inch
kV	kilovolt
kVA	kilovoltampere
kW	kilowatt
kW/m^2	kilowatt per square meter
m^3/s	cubic meters per second
µm	micrometer
min	minute
mm^2	square millimeter
MPa	megapascals
mph	miles per hour
mW	megawatt
n/a	not applicable
nm	nanometer
nm/s	nanometers per second
psf	pounds per square foot
psi	pounds per square inch
s	second
sf	square foot
V	volt

Metric Conversions

FEMA is committed to the Federal Government's transition to the metric system; however, although the fire engineering discipline has adopted the metric system as the standard for measurement, the majority of the engineering community currently uses English units. As a result, all measurements in this report, with the exception of temperatures, are presented in English units. Because the metric system may eventually become the standard for measurement in the United States, approximate metric conversions are presented in the following table to promote familiarity with that system. A critical component of unit conversion is rounding. Readers who convert English units to metric units using the factors shown here should be aware of differences resulting from rounding.

Quantity	To Change English Units	To Metric Units	Multiply English Units By:
Length	inch (in) foot (ft) mile (mi)	millimeter (mm) meter (m) kilometer (km)	25.4000 0.3048 1.6093
Area	square foot (ft^2) acre (a)	square meter (m^2) square meter (m^2)	0.0929 4,046.8564
Volume	gallon (gal) cubic foot (ft^3)	liter (L) cubic meters (m^3)	3.7854 0.0283
Pressure	psf (lb/ft^2) psi (lb/in^2)	Pa kPa	47.8803 6.8947
Weight	pound (lb)	kilogram (kg)	0.4536
Flow	cfs (ft^3/sec)	ips	28.3168
Velocity	lps (ft/sec) mph	mps kph	0.3048 1.6093
Temperature	To change degrees Fahrenheit (°F) to degrees Celsius (°C) use the following formula: °C = 5/9 ()F–32)		